Influence of Damage and Degradation on Breakdown Voltage of NM Cables

Final Report

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TABLE OF CONTENTS

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The technical panel consisted of the following members:

- John Allen, ATF Fire Research Laboratory
- Vyto Babrauskas, Fire Science and Technology Inc.
- Bill Burke, Electrical Division Director, NFPA
- Anthony Hamins, Building and Fire Research Laboratory, NIST
- Mark Hilbert, New Hampshire Department of Safety
- Doug Lee, Consumer Product Safety Commission
- Wei-Jen Lee, University of Texas at Arlington
- Dave Mercier, Southwire Company
- John Sleights, Travelers Insurance

Executive Summary

According to the fire incident data from 2003 to 2007[5], there is an average of 50,900 fires annually in homes related to electrical failure or malfunction. An NFPA analysis of home fire statistics shows that electrical fires result in an average of 490 civilian deaths, 1140 injuries, and $1.3B in direct property damage every year. Approximately 57% of these fires originate from wiring and related equipment[1]. Some key causes of fires due to electrical wiring result from arcing and loose connections. These conditions may develop from improper installation or maintenance and are exacerbated over time from exposure to high temperature and humidity.

Currently, the National Electrical Code (NEC®) requires the use of arc fault circuit interrupters (AFCIs) in the electrical panel of a dwelling unit to protect against arcing faults. The 2011 National Electric Code (Article 210.12) allows the use of an AFCI located in the first electrical receptacle of a residential circuit in lieu of an AFCI located inside the electrical panel as an exception. However, the wiring from the circuit panel to the first receptacle (home run) is required to be protected from damage during installation per code requirements.

In preparation for the 2014 Edition of the National Electrical Code® (NEC®), several proposals were made to revise Section 210.12 for arc-fault circuit-interrupter protection to permit a listed outlet branch circuit type arc-fault circuit interrupter (OBC AFCI) to be installed at the first outlet on the branch circuit under certain conditions of installation. Two questions have arisen regarding the use of an OBC AFCI: one, under what conditions, if any, would a conventional circuit breaker mitigate an arcing fault (with respect to the criteria in UL 1699); and two, if carbonized path arcing may occur within the home run given potential for installation damage and subsequent cable aging. The first question has been addressed in three UL research reports[2,3,28]; and the second question is addressed in this report.

This research investigation was undertaken to study the influence of damage (*i.e.*, damage occurring during installation of the electrical wiring) and subsequent degradation of the dielectric breakdown voltage of the cable insulation. Dielectric breakdown is a primary cause of the formation of a carbonized path between conductors, which can result in a carbonized path arcing fault.

This project investigated commercially available 14-gauge, two-conductor (14-2) type NM (NEC 334.2) cables with bare ground conductor, from five different manufacturers. Two cables were selected after characterizing their insulating materials using a combination of analytical techniques and measurement of dielectric strength. The selected cable insulations had distinct plasticizer and additives, and measured dielectric strength values.

Two types of damage scenarios were investigated in this work, representative of the information found in the literature, associated with installation activities: (*i*) inadvertent hammer blow to the cable outer jacket; and (*ii*) compression of the insulation from over-driving staples through the outer jacket. In both cases, methods were developed to provide repeatable and controlled damage to the cable. Other types of damage scenarios like pest infestation are not discussed in this report due to lack of data and quantitative

test methods. The dielectric breakdown voltage of the cable insulation was tested after applying the damage conditions. The results showed that such damage to cables during installation may reduce the NM cable insulation breakdown voltage from over 20kV (in undamaged cables) to less than 1kV, and below the 5kV failure threshold set by UL719 and other related safety standards. Though carbonized arcing will not occur until the breakdown voltage falls below 170V, lowered breakdown voltage render the NM cable susceptible to further breakdown damage from voltage surges, which occur more frequently at or below 6kV. Thus, as the insulation breakdown voltage falls, the potential of a carbonized path and subsequent parallel arcing fault forming in the cable increases.

Another focus of this project was the influence of thermal aging of NM cable on its dielectric breakdown voltage. Selected cable samples were exposed to a range of elevated temperatures up to 150°C. This maximum temperature was selected to ensure that the cable insulation (plasticized PVC) does not undergo dehydrochlorination[4], but will still induce plasticizer loss, which is a major degradation pathway. The samples were weighed and dielectric breakdown voltage tests were performed at regular intervals. The project also investigated the combined effect on initial damage followed by thermal aging on the breakdown voltage. The influence of combined initial damage followed by thermal aging resulted in faster reduction of dielectric breakdown voltage of the cable insulation.

To evaluate the probability of arcing when NM cables have lowered breakdown voltages, hammer-damaged and aged NM cable samples were tested per UL1449 (Standard for Surge Protective Devices). This test showed despite a breakdown voltage lower than the surge voltage (using 6kV surges on samples with breakdown voltages below 5kV), 9% of the hammer-damaged and 2% of the hammer-damaged and then aged samples exhibited arcing after the surge occurred. All of these observed arcs were approximately 1.7ms in duration, meaning that the arcing was longer than the surge event (*i.e.*, supplied by 120VAC), but self-extinguished within a single AC half-cycle. These events did not have enough energy to ignite NM cable insulation and were not sustained for more than one half-cycle, a duration that is not expected to trip an AFCI and is shorter than the UL1699 eight half-cycle criterion. To evaluate whether subsequent damage would increase arcing duration or sustainability, samples were tested using 300 voltage surges to understand how likely the repeated voltage surge and arcing may result in sustainable arcing and ignite the NM cable insulation. But these tests did not show any sustained arcing.

The test results indicate that the probability of sustained arcing and ignition is low for hammer-damaged NM cable. The results also show that though a carbonized path may eventually be formed, this path formation did not lead to subsequent ignition of the cable jacket or surrounding materials, and self-extinguished after a short period of arcing.

THE INFLUENCE OF DAMAGE AND DEGRADATION ON THE BREAKDOWN VOLTAGE OF NM CABLES

Introduction

Electrical Fire Incident Data

According to published reports and research articles, the number of residential electrical fires ranges from 28,300 to 60,000 per year[5], depending on the source of the data. Since the terms ‘electrical fire’, ‘electrical wiring’, and ‘electrical equipment’ are not rigorously defined in literature, quantitative data varies among sources. Approximately half of all electrical fires can be attributed to installed wiring and related equipment[6]. Figure 1 shows the reported sources of electrical fires.

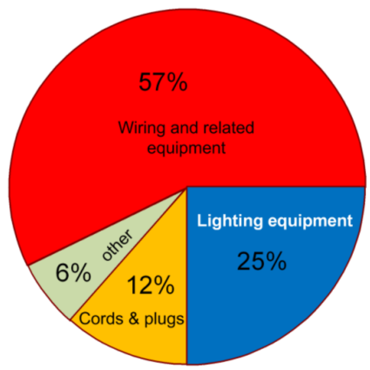


Figure 1 - Source of electrical fires

Table 1 provides a summary of the statistical data from a number of sources. Several investigations have identified that key contributors to electrical fires are wire degradation, damage[7], improper installation, and excessive electrical circuit load[8].

Table 1 - Electrical fire statistics

Source of data	Average number of electrical fires per year	% of fires caused by wiring and equipment	Reference
National Fire Protection Association	50,900	57	1
US Fire Administration	28,300	47	5
Other	32,000 to 60,000	N/A	7

Table 2 summarizes the causes of electrical fires and provides references for the data.

Table 2 – Possible faulty conditions of electrical fires

Faulty condition	Description	Reference
Wire degradation	Aging over time under high temperature, high humidity and other environmental exposures	6, 8
Excessive load	Load greater than the rated current under specific temperature	8
Voltage surge	High Voltage may result in arcing and cause fire	15
Bad connection	High resistance connection in receptacles, junction boxes etc.	8
Mechanical damage in installation	Over compression by stapling the NM cable with high pressure, staple puncture, cracking by bending the NM cable with sharp angle, abrasion and hammer impact	22, 23
Damage due to pest infestation	Damages caused by rodent and other pests	8

The National Electrical Code (NEC®) requires the use of arc fault circuit interrupters (AFCIs) in the home electrical panel to protect against arcing faults. The 2011 NEC (Article 210.12) allows the use of an AFCI built into the first electrical receptacle after the circuit panel in lieu of an AFCI in the electrical panel provided the wiring from the circuit panel to the first receptacle (home run) is installed in a metal conduit (or similar type of raceway) to protect it from damage during installation.

NM cable is used extensively in the USA, with approximately 8 billion feet of NM cable sold in 2007, and is used in nearly 75% of new single family homes[9]. Thus, the NEC requirement would exclude the use of the receptacle-based AFCI in many communities where NM cabling is permitted without the use of protective metal conduit.

The research investigation described in this report was undertaken to study the influence of damage (*i.e.*, from installation) and subsequent degradation on the dielectric breakdown voltage of NM cable insulation, since this is an important electrical property relative to carbonization of electrical insulation and potential for ignition.

Objective

The objective of this project was to develop data on the influence of damage during installation and degradation of NM cable's insulation relative to its dielectric breakdown voltage.

Scope

- This investigation was focused on commercially available NM cables in USA.
- This investigation did not develop data to predict service life of the NM cables under installed field conditions.

Project Plan

A technical plan to meet the research objectives was developed as follows:

- Task 1. Literature search.
- Task 2. Sample selection.
- Task 3. Installation damage assessment.
- Task 4. Aging and service life assessment.
- Task 5. Combined installation and aging degradation.
- Task 6. Technical report.

The research report is presented herein.

Research Report

Task 1 — Literature Search

The literature search for this project focused on (i) types of electrical wiring used in homes; extensive use of NM cable in the US; the typical construction of NM cable; and (ii) data for damage and degradation of electrical wiring.

Electrical Wiring in US Homes[10]

There are several types of electrical wiring permitted in homes by the NEC. These include (i) separated conductors; (ii) armored cable; and (iii) non-metallic (NM) cable. A brief background on these wiring systems is presented herein.

Separated Conductors

Beginning in Thomas Edison's timeframe, the original residential wiring systems used conductor insulation made of gum-rubber. This "rubber" insulation was a mixture of ingredients including vulcanizing agents containing sulfur for curing. These various additives, especially sulfur, had a very corrosive effect on the copper conductor, so the copper had to be tin-coated.

During the 1950's, the wire industry began transitioning residential wire insulation from rubber to the newly developed polyvinyl chloride (PVC) thermoplastics with the extensive use of low molecular weight ester plasticizers (typically based on phthalic or trimellitic anhydride and various short chain alcohols (from C8 to C15). Plasticized PVC compounds have advantages over vulcanized rubbers in that they did not suffer from the brittleness and cracking with age that was typical of the older rubber insulation. It also did not contain sulfur additives that could damage the conductor, so the copper did not have to be tin-coated. Another advantage of plasticized PVC compounds is that there were more options with color pigmentations, and the color tended to hold its pigmentation better than rubber, which often had a painted wrap that discolored with time. In the mid-1980's, 90°C rated wire began replacing the 60°C and 75°C wire typical of the earlier installations.

Today the separated conductor type of electrical wire is mostly used in the building electrical systems that require metal tube or metal conduit for wire protection. The installation procedure is to first install the metal tubes or conduits as the wire protection in the electrical distribution system, and then feed the insulated electrical wires through the metal tubes or conduits for electrical connections.

Armored Cable

Armored cable (AC) was first Listed in 1899 for the Sprague Electric Co. of New York, and was originally called "Greenfield Flexible Steel-Armored Conductors," after one of its inventors, Harry Greenfield. There were originally two experimental versions of this product, one called "AX" and the other "BX," with the "X" standing for "experimental." The "BX" version became the one that eventually got produced, and hence the name “BX” stuck, which also became the registered trade name of armored cable for General Electric, which later divested this business to Sprague Electric.

Armored cable, or BX, first appeared in the 1903 NEC, but did not start becoming popular until around 1930, and is still a popular wiring method today. AC cable is described in Article 320 of the NEC. The armor of AC cable systems is tested for grounding and can provide a suitable equipment grounding path. AC cable made after 1959 requires an aluminum bonding strip under the armor to help improve the conductivity of this path. Although originally produced with steel armor, in the late 1980’s lightweight aluminum armored AC cable first became Listed in accordance to NEC requirements.

Nonmetallic Cable

Nonmetallic-sheathed cable, or NM for short, was first Listed and described in the NEC in 1926, but it was invented a few years earlier by Rome Wire Company in 1922 in Rome, NY, and marketed under the trade name “Romex®.” Romex® is now a registered trademark of Southwire Company of Carrollton, GA[11]. Early NM cable had their individual conductor insulation wrapped in a cotton braid that was impregnated with either a varnish or tar-like substance for moisture protection.

Around 1950, synthetic spun rayon was being permitted to replace the cotton thread in the jacket braid. Then in the early 1960’s, thermoplastic began replacing the braided jacket altogether, and by about 1970, most all NM cable had a compounded PVC outer jacket, even though a braid was still permitted until 1984. Also in 1984, NM-B cable was developed and required to have 90°C rated individual conductors, and a 75°C outer jacket.

Until the early 1960’s, most NM cable for residential use did not have a grounding conductor. However, changes in the 1962 Code that mandated equipment grounding for all branch circuits popularized the use of NM cable with ground. Earlier versions of NM cable with ground permitted the grounding conductor to be one or even two sizes smaller than the current carrying conductors. For example, a 16 AWG ground wire was permitted for 14 and 12 gauge copper NM, and 14 AWG ground for 10 gauge copper NM. In 1969, new requirements no longer permitted an undersized grounding conductor for 14, 12 and 10 AWG NM cable.

A survey of residential cable usage shows that NM cable is used extensively in the USA, with approximately 8 billion feet of NM cable sold in 2007, and is used in nearly 75% of new single family homes[9].

Residential Electrical Cable Installation

In the United States, the indoor residential electric power wiring system is typically considered to start at the electric power meter installed by the utility company, and includes all wiring within the home. Heavy gauge cables (*i.e.*, 2/0 AWG cable) connect the electric power meter to the service panel box. The electric power is then distributed to each room through circuit breakers with NM cable or other types of cables depending on the local Code.

NM Cable Installation

1. A typical single-family house in US has about 2,500 feet of NM cable in the electrical power system. Because the distance between the service panel box and any room in a house is much longer than 5 feet, it is necessary[12] to secure the NM cable when distributing the electric power to different areas in the house. For the purpose to quantitatively assess the NM cable damage in the installation process, this project follows the NEC and NEMA[13,14] guidelines when installing the NM cable test samples.NEMA RV2 2008. Protection for cable in concealed locations: where NM cable is run through studs, joists or similar wooden members, the outer surface of the cable must be kept at least 32 mm (1.25 inches) (from the edges of the wooden members, or the cable should be protected from mechanical injury. This latter protection can take the form of metal plates (such as spare outlet box ends) or conduit
2. NEC 2011 300.4**.** In both exposed and concealed locations, where cables are installed through bored holes in joists, rafters, or wood framing members, the holes shall be bored so that the edge of the hole is not less than 1¼ inch from the nearest edge of the wood member. Where this distance cannot be maintained, or where screws or nails are likely to penetrate the cable, it shall be protected by a steel plate at least 1/16" thick and of appropriate length and width.
3. NEC 2011 334.30. NM cable shall be supported within 300 mm (1 foot) of every box or fitting, and at intervals of no more than 1.4 m (4.5 feet).
4. 2- NEMA RV2 2008. Conductor NM cable should never be stapled on edge.
5. NEC 2011 334.12. NM cable should not be embedded in masonry, concrete, adobe, fill or plaster. NEC 300.7. Portions of raceways and sleeves subject to different temperatures (where passing from the interior to the exterior of a building) shall be sealed with an approved material to prevent condensation from entering the service equipment.
6. NEC 300.22. Type NM cable shall not be installed in spaces used for environmental air, however NM is permitted to pass through perpendicular to the long dimension of such spaces.
7. NEMA RV2 2008. Wire should be selected, but de-rated in current carrying capacity to 60°C.
8. NEC 2011 334.15. Cable shall be protected from physical damages when necessary by rigid metal conduit, intermediate metal conduit, electrical metal tubing, Schedule 80 PVC conduit, Type RTRC marked with suffix –XW, or other approved means.
9. NEC 2011 334.12. NM, NMC and NMS should not be used in wet and dump locations.

These guidelines were used to develop data on damage and degradation of the electrical performance of NM cables in this project.

Potential of Damage to Cable Insulation from Common Installation Practices

The most common method of installing NM cable is to secure the NM cable with staples onto wooden framing members. The tools used to install NM cable include hammer, manual staple gun, and electric staple gun. Figure 2 shows a picture of some NM cable installation tools. Because of the accuracy and applied force of the NM cable installation tools, there is a potential of damage to the NM cable during a home installation. According to the inspection reports[22,23], the most common types of cable damage include cable puncture, cable over-compression and hammer impact. Electrical Code inspection organizations record many NM cable installation code violations every year, but there are few quantitative reports which provide details of how likely the NM cable can be damaged during installation, and what level of damage the NM cable may suffer.

Figure 2 - NM cable installation tools

There are several kinds of staples used in the installation of NM cables as shown in Table 3. These include bare metal staples, metal staples with plastic insulation, and plastic staples with metal pins. Potential damage to the NM cable may occur during installation depending the staples and tools used (Table 3).

Table 3 - NM cable installation tool and damage mechanisms

Stapler / Tool	Metal staple 	Metal staple with plastic insulation 	Plastic staple with metal nails 
Hand hammer	Damage due to (I) direct hammer impact on cable; and (ii) over driving the staple	Damage due to direct hammer impact on cable	Damage due to direct hammer impact on cable
Stapler	Damage due to (i) puncturing of insulation; and (ii) over driving the staple	Damage due to puncture	N/A

Damage to Cable Insulation from Voltage Surges

Francois Martzloff investigated residential voltage surges in the 1960s and his research work is still used as an important reference for expected surge voltages for residential electricity distribution system design and test. Figure 3 shows frequency data on voltage surges from Francois Martzloff and other sources[15].

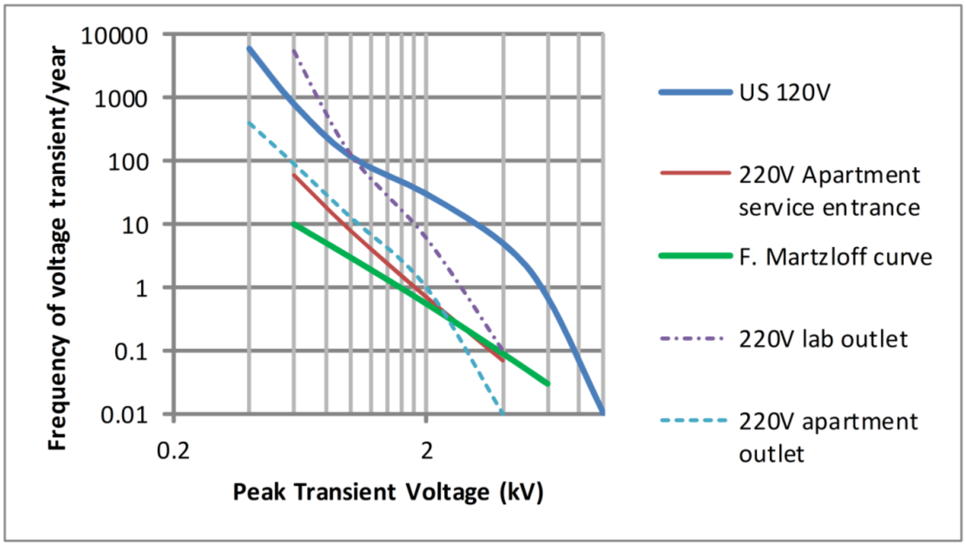


Figure 3 - Residential voltage surge statistics.[15]

According to the data, the probability of 6 kV and higher voltage surge is relatively low in the residential electricity distribution system, with less than one surge event greater than 6kV expected per year. This coincides with requirements in electrical wiring test standards for the dielectric breakdown voltage for home electrical wiring insulation materials. It may be observed from the figure that the frequency of voltage surge in the USA (blue line in Figure 3) of 2 kV is 15 per year and surges of 1 kV are more than 100 per year.

Cable Insulation Degradation

In addition to either mechanical damage or from voltage surges, the NM cable insulation may experience subsequent degradation of electrical safety performance during its service life from a number of factors that include the following:

- **High-temperature exposure due to overload and/or increased ambient temperature.** Exposing to elevated temperatures can cause accelerate loss of additives, including stabilizer(s) and plasticizer(s). This is likely to reduce the dielectric strength of the insulation.
- **High humidity exposure.** Exposure to humidity may result in moisture penetration into NM cable insulation, which could increase the insulation leakage current and reduce the insulation breakdown voltage.

- **Exposure to salt and other contaminants.** Salt and other contaminants or pollutants may penetrate into the NM cable insulation and accelerate NM cable insulation decomposition and thus will increase the insulation leakage current and reduce the insulation breakdown voltage.
- **UV exposure.** Ultraviolet radiation has higher energy than visible spectrum photons. If the UV photon energy is higher than the insulation additive activation energy, UV exposure will accelerate the loss of insulation additives including stabilizer and plasticizer, and depending on the temperature material decomposition may also occur.

It is assumed that thermal aging caused either by high ambient temperature or overload is a dominant factor that accelerates cable insulation degradation over time. This degradation may be further exacerbated by high humidity and exposure to salts, contaminants or pollutants. Based on the lack of availability of field samples for calibration and the fact that little residential electrical wiring is exposed to UV in the real world applications, the scope of this project was limited to investigating only the effect of thermal degradation of cable insulation materials. UV/visible radiation exposure to conductor insulation is more likely at splice points or junction boxes (where the outer jacket is removed), but this is also considered outside the scope of this project.

There are many technical papers in the area of electrical insulation aging and degradation,[16,26,17] but there was lack of data on correlation between cable insulation degradation and electrical performance such as reduction of the dielectric strength.

Literature Search Summary

Based upon the literature search, a focus for this research project was defined as follows:

- Select NM cables in the investigation since NM cables are used commonly in residential buildings in the USA, and that the insulation used in NM cable are the same or similar to the insulation used in other types of electrical wiring (*i.e.*, plasticized PVC).
- Consider mechanical damage conditions encountered in installing NM cables, such as inadvertent hammer blows and improper stapling.
- Consider only temperature-related degradation conditions of the NM cable insulation materials that may occur due to overload or high ambient temperature.

Task 2 — NM Cable Sample Selection

Five major manufacturers of NM cables, commercially available in the USA, were selected initially for the research project. The test cables were designated as A, B, C, D, and E, representing the five manufacturers. The cables were screened using analytical techniques and dielectric breakdown testing to select two NM cables with distinct cable characteristics.

NM Cable Insulation Characterization

NM cable insulation materials from five manufacturers were characterized with respect to their thermal, chemical, and electrical properties. Based upon results, two cables with distinct properties were identified for further evaluation in this research investigation.

Thermal Characterization – Thermogravimetric Analysis

Thermogravimetric analysis (TGA) was performed on the NM cable insulation materials to develop information on the thermal degradation of cable insulation under controlled temperature conditions.

In the temperature scan mode, the TGA furnace temperature is increased at a constant rate in air or nitrogen environment, and the insulation sample weight is monitored. Figure 4 through Figure 8 show the TGA weight loss rate results in air environment and at 20 ^{0}C/min scan rate for ten different NM cable insulation materials from the five NM cable samples. The results for white insulation material are on the left hand side, and results for the black insulation are on the right hand side.

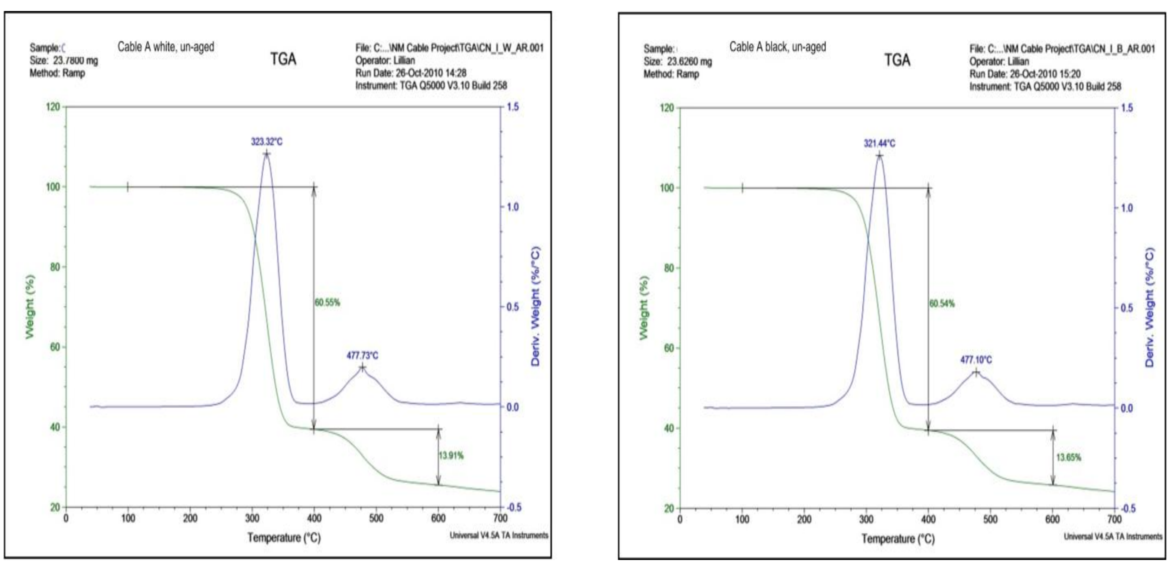


Figure 4 - TGA from Cable A Insulation

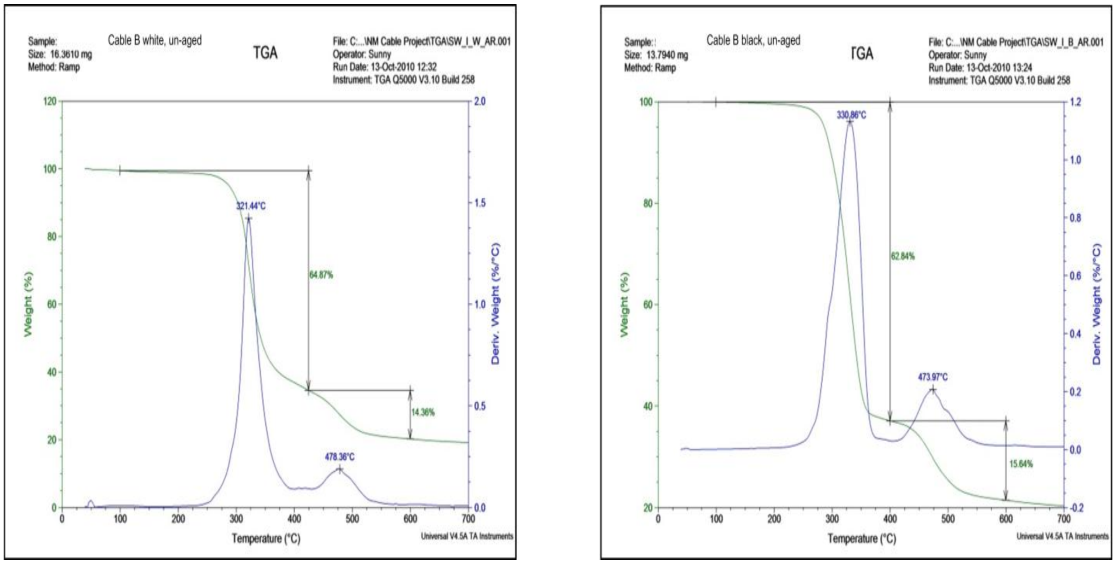


Figure 5 - TGA from Cable B Insulation

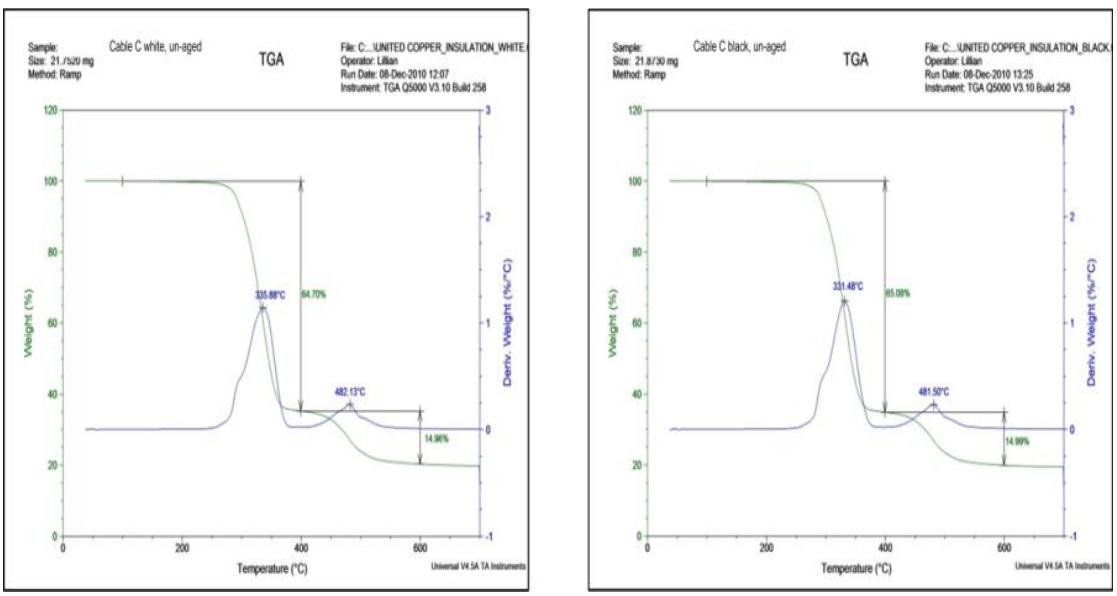


Figure 6 - TGA from Cable C Insulation

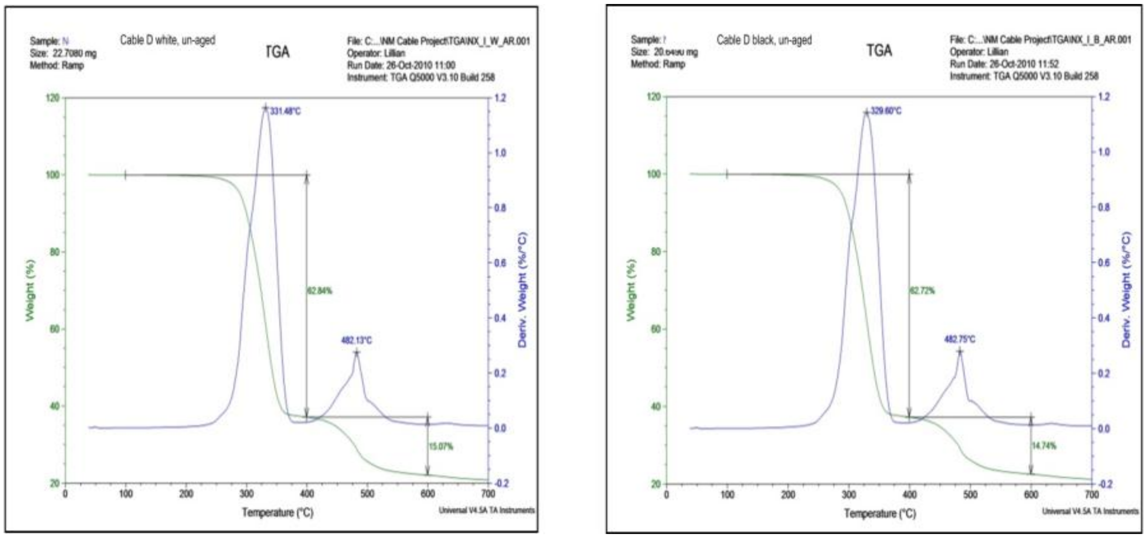


Figure 7 - TGA from Cable D Insulation

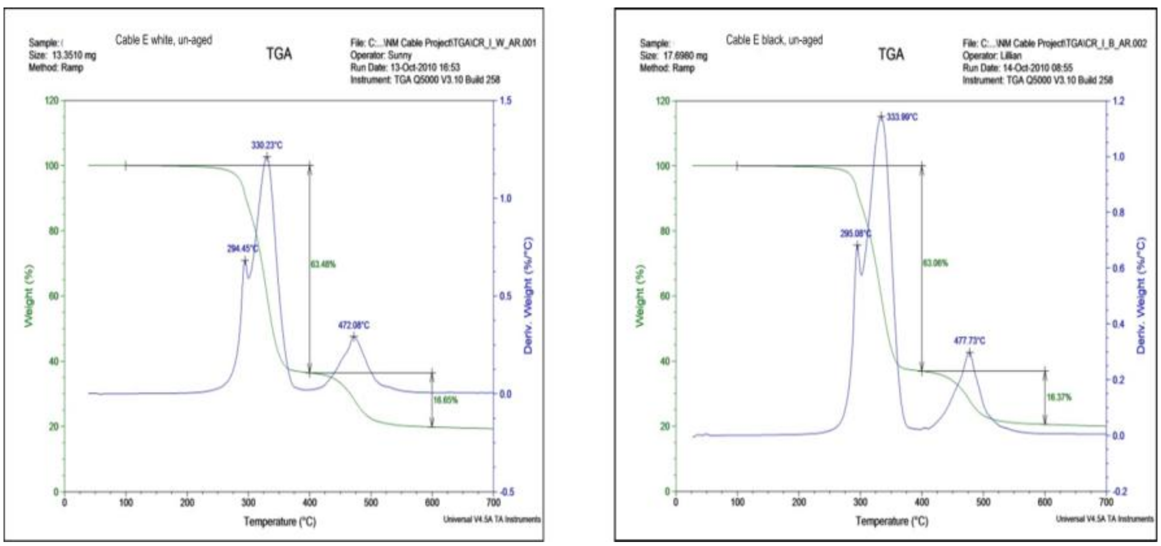


Figure 8 - TGA from Cable E Insulation

The TGA data from the insulation materials (white and black samples) of the NM cables depict some distinct behavior. For example, Cables B, C, and D show a slight curvature in the first peak indicating that the weight loss rate is a combination of thermal degradation from multiple insulation components. The weight loss rate of Cable E is different from others as it displays three main peaks, and an earlier first peak indicating a more volatile insulation component. Because the TGA profile can be a convolution of thermal decomposition of many chemical compounds, these differences point to the presence of different plasticizer compounds used in the different insulations. The thermogravimetric data from the selected NM cables are summarized in Table 4, which indicates that Cable E is quite different from the others.

Table 4 - Weight loss rate peak temperature

	1st peak (°C)	2nd peak (°C)	3rd peak (°C)
Cable A white	N/A	323.32	477.73
Cable A black	N/A	321.44	477.10
Cable B white	N/A	321.44	478.36
Cable B black	N/A	330.86	473.97
Cable C white	N/A	335.88	482.13
Cable C black	N/A	331.48	481.50
Cable D white	N/A	331.48	482.13
Cable D black	N/A	329.60	482.75
Cable E white	294.45	330.23	472.08
Cable E black	295.08	333.99	477.73

The TGA equipment may also be programmed to obtain insulation weight loss data exposed to a constant temperature (isothermal mode). The weight loss data acquired in this manner can be used in estimating the activation energy of different chemical components in the insulation. It also aids in the understanding of the temperature-dependent accelerated aging effects when using a thermal chamber to evaluate the insulation material thermal degradation.

Figure 9 depicts weight loss of four different insulation materials. The chart shows that the insulation material weight loss is a nonlinear function of time, and insulation materials from different brands of NM cable have different weight loss rates at a particular TGA temperature. The nonlinear characteristic observed in the weight loss data is indicative of multiple thermal decomposition processes in the insulation material

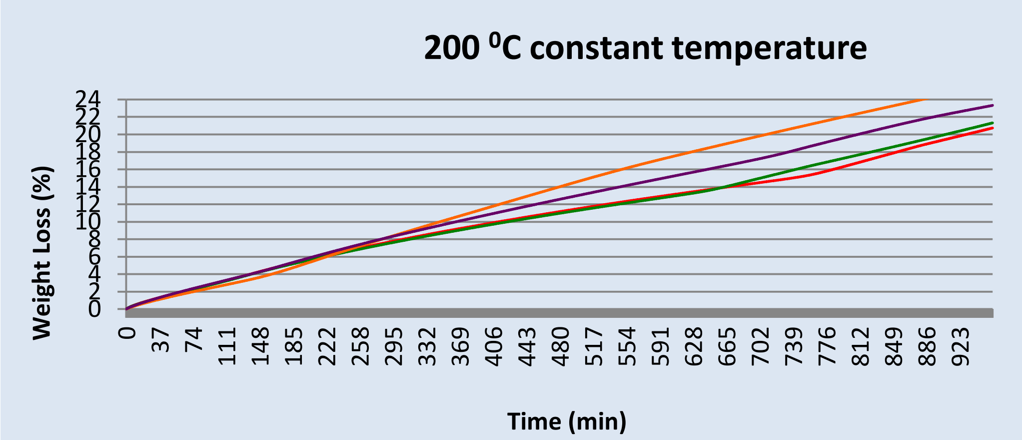


Figure 9 - Constant temperature TGA data. The red trace is cable B white insulation weight loss, the green trace is cable B black insulation weight loss, the purple trace is cable E black insulation weight loss, and the orange trace is cable E white insulation weight loss.

Chemical Characterization – FTIR analysis

The insulation materials from the NM cables were chemically analyzed with an FTIR (Fourier Transform Infrared) analyzer using the attenuated total reflectance method.

Figure 10 shows the test results for Cable B and Cable E insulation (in blue) for the white insulation. The black insulation also has similar IR characteristics. The plasticizers used in the cables were identified through comparison to a chemical library (in red).[18] The FTIR results indicate that Cable B has a phthalate plasticizer, while Cable E has trimellitate plasticizer. These plasticizers exhibit significantly different properties as will be discussed in the following sections. The plasticizer data for each NM cable are summarized in Table 5.

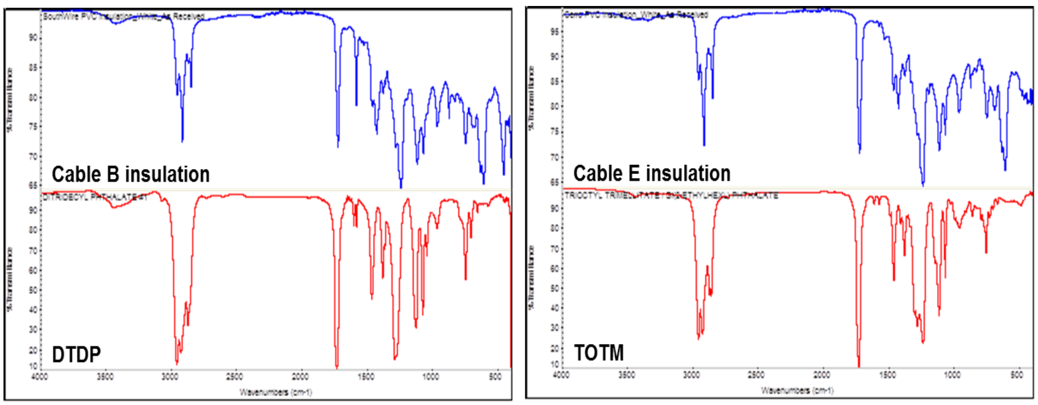


Figure 10 - FTIR spectrum for Cable B and Cable E insulation

Table 5 – Cable Insulation Plasticizers

Cable	Plasticizer
Cable A white	Phthalate
Cable A black	Phthalate
Cable B white	Phthalate
Cable B black	Phthalate
Cable C white	Trimelliate
Cable C black	Trimelliate
Cable D white	Trimelliate
Cable D black	Trimelliate
Cable E white	Trimelliate
Cable E black	Trimelliate

Table 6 – Property Comparison of Selected Phthalate and Trimellitate Plasticizers Di-iso-nonyl phthalate (DINP), Di-tri-decyl phthalate (DTDP), Tri-2-ethylhexyl Trimellitate (TOTM)

Plasticizer	**DINP**	**DTDP**	**TOTM**
Molecular Formula	$C_{26}H_{42}O_4$	$C_{34}H_{58}O_4$	$C_{33}H_{54}O_6$
Appearance@25°C	Clean liquid	Clean liquid	Clean liquid
Molar Mass (Molecular weight)	418.61 g/mol	530.82 g/mol	546.79 g/mol
Melting Point	-43°C	-37°C	-38°C
Boiling Point at 760mm Hg	405.7°C	508.2°C	414°C
Vapor Pressure at 25°C	8.61×10^{-7} mmHg	3.63×10^{-8} mmHg	4.10×10^{-14} mmHg

From Plastics Additives[19] "trimellitate esters are distinguished by high thermal stability and low volatility". This is evidenced by the low vapor pressure in comparison to the two common phthalates listed in the table. The trifunctional ester in trimellitates provides superior permanence and dispersion in polar PVC formulations. Note that other properties of the phthalates and trimellitates are quite similar (molecular weight, boiling point and water solubility) so the key property is vapor pressure.

Insulation Breakdown Voltage Test

As was shown in the literature discussion conducted in Task 1 and illustrated in Figure 3, significant surge voltages are encountered in home wiring below 6 kV. There are several breakdown voltage test standards for dielectric strength evaluations. Since the equipment used in the breakdown voltage test is calibrated for RMS values at 60Hz, all breakdown voltage measurements cited in this report are RMS values[20].

When performing breakdown voltage tests in air, it was observed that the air is ionized and generates a corona when the electric field strength is greater than the air breakdown threshold of 3 kV/mm. Since high speed particles in the corona can preheat the sample and weaken the wire insulation, it impacts the measurement of the breakdown voltage. Thus, the test fixture was redesigned to reduce the impact of the corona on the measurement, as it was anticipated that the breakdown voltage of the insulation materials to be greater than 3 kV. The test fixture is depicted in Figure 11. The test fixture was designed to test a single-insulation conductor (without the NM cable outer jacket).

Figure 11 - Fixture for the NM cable breakdown voltage test

The sample preparation procedure was as follows:

1. Pull out the conductors from the NM cable outer jacket
2. Strip insulation by a half inch at one end of the conductor
3. Bend the conductor around a quarter inch diameter rod
4. Vary the voltage across the conductor until insulation breakdown occurs. Breakdown of the insulator is detected when the leakage current reaches 10 mA.

A schematic of the cable sample under test and the test probe during the breakdown voltage test is depicted in Figure 12.

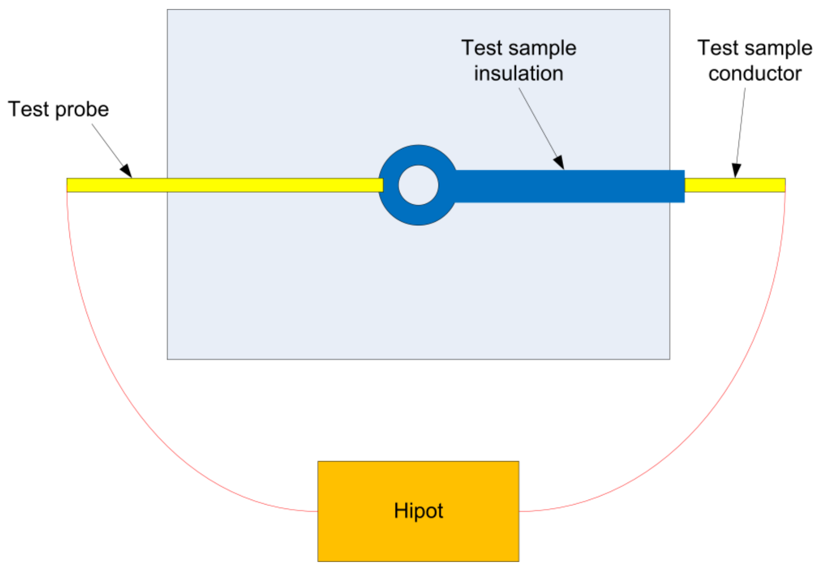


Figure 12 – Cross-section of the Teflon fixture for the NM cable breakdown voltage test

Assessment of the NM cable insulation breakdown voltage

To develop statistically significant data, 30 specimens were tested on both the black and white insulation for each type of the NM cables, except for Cable C (29 white specimens and 29 black specimens). The average, minimum, and maximum values of the breakdown voltage are depicted in Figure 13.

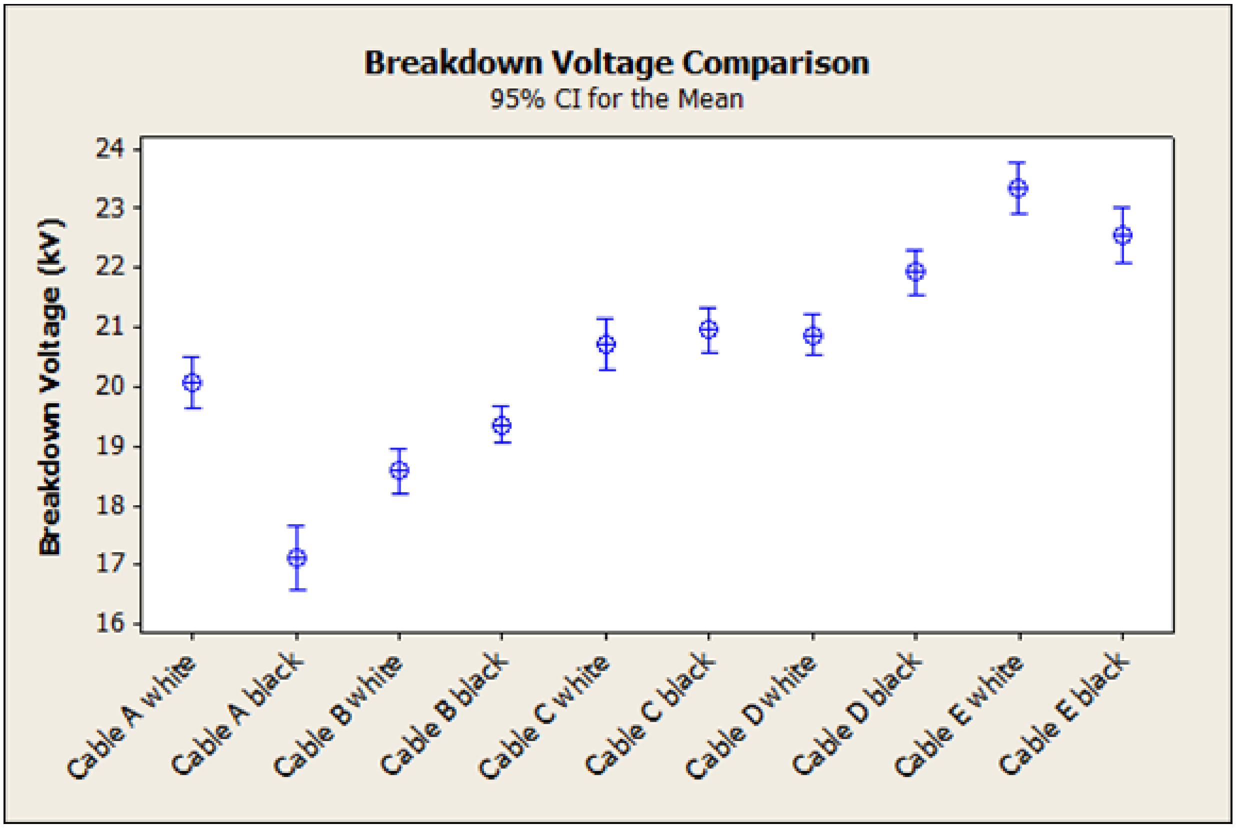


Figure 13 - Average breakdown voltage comparison

The average breakdown voltages along with the standard deviation are summarized in Table 7. Pearson analysis[21] was applied to determine if insulation thickness had an influence of breakdown voltage, and the result showed that insulation thickness of the selected NM cables was not correlated to the measured dielectric breakdown voltage.

The results of dielectric breakdown voltage were further analyzed to assess if the difference in measurements were statistically significant. Figure 14 through Figure 18 show the breakdown voltage distribution for the black and white insulation of Cables A, B, C, D and E, respectively. The breakdown voltage results indicate that the distributions are normally distributed (*i.e.*, Gaussian).

Table 7 - Average breakdown voltage and standard deviation

Sample Type	Average breakdown voltage (kV)	Insulation Thickness	Number of samples	Standard Deviation (kV)
Cable A white	20.1	0.35	30	1.15
Cable A black	17.1	0.37	30	1.42
Cable B white	18.57	0.40	30	1.04
Cable B black	19.36	0.41	30	0.81
Cable C white	20.7	0.40	29	1.13
Cable C black	20.95	0.39	29	1.02
Cable D white	20.87	0.38	30	0.93
Cable D black	21.93	0.38	30	1.02
Cable E white	23.34	0.39	30	1.15
Cable E black	22.54	0.39	30	1.23
			Pearson coefficient	0.096
			P value	0.791

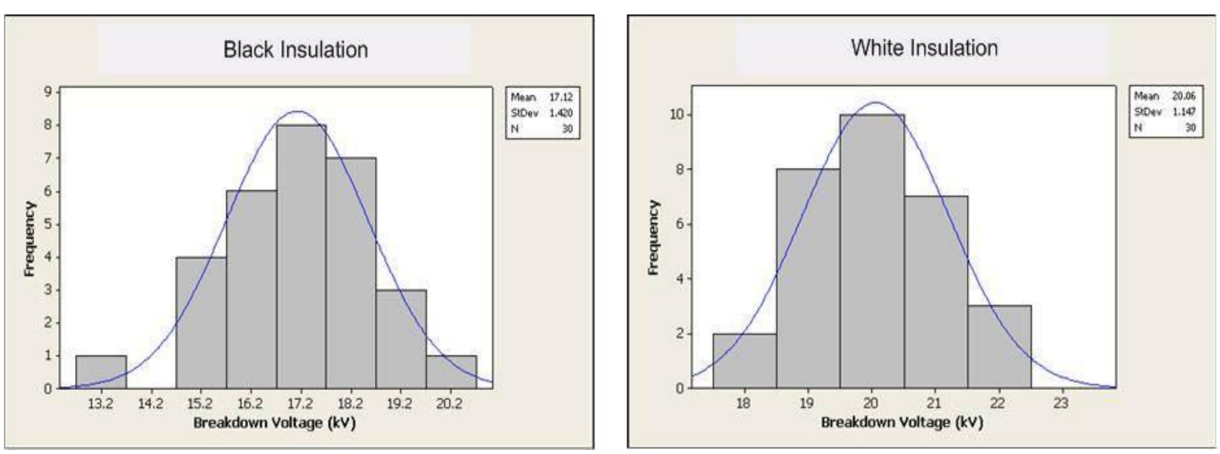


Figure 14 - Cable A breakdown voltage distribution

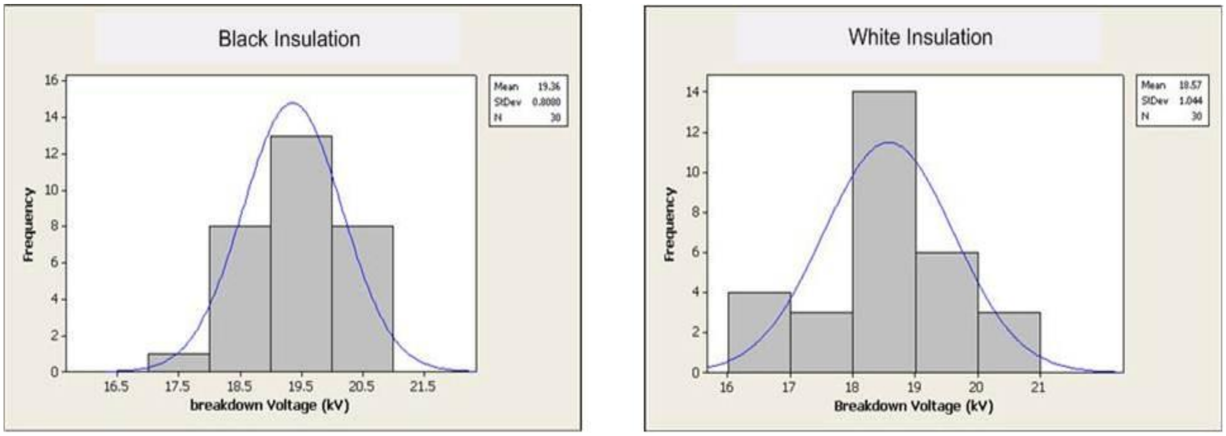


Figure 15 - Cable B breakdown voltage distribution

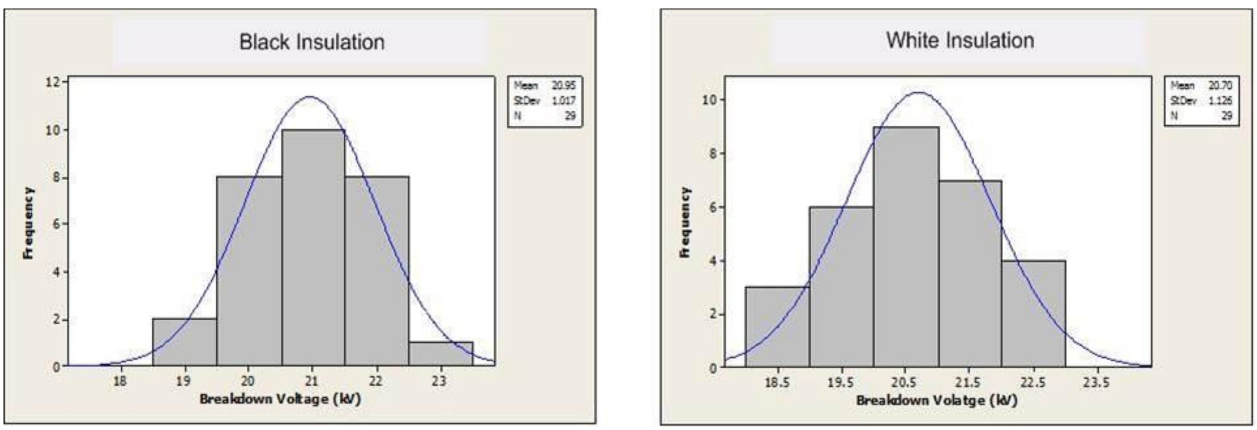


Figure 16 - Cable C breakdown voltage distribution

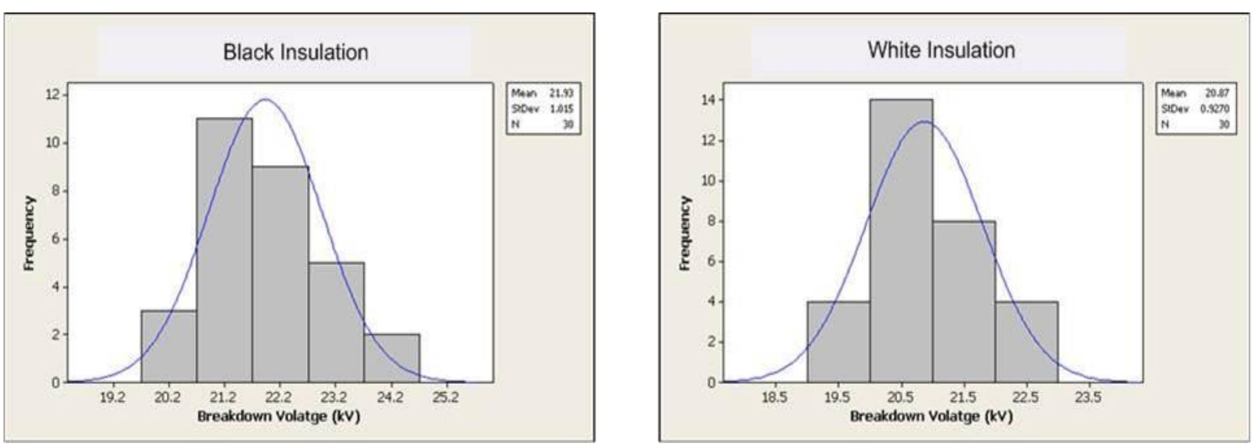


Figure 17 - Cable D breakdown voltage distribution

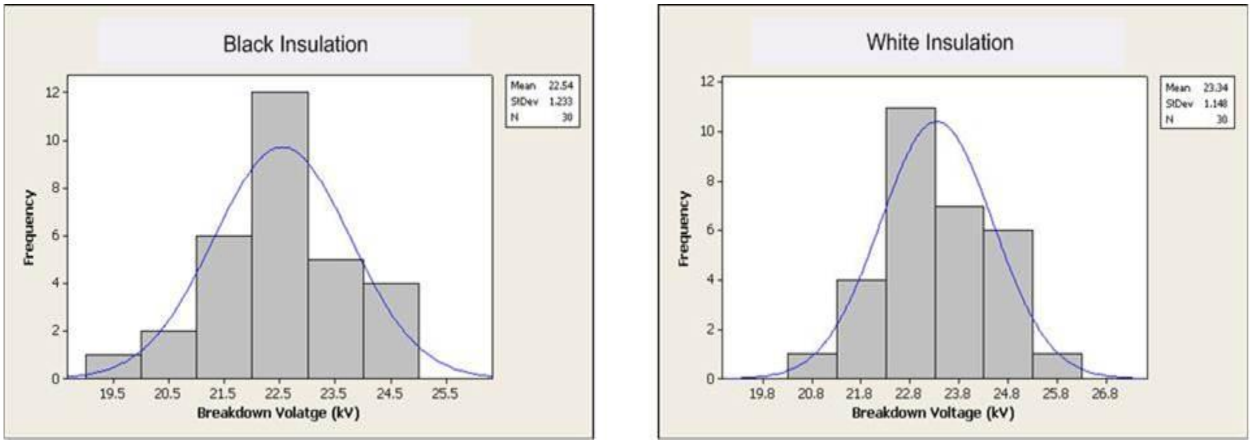


Figure 18 - Cable E breakdown voltage distribution

To verify if two different insulation materials may have different breakdown voltages[21], the following equation was used to calculate the breakdown voltage difference between two different types of NM cable insulation compositions:

$$\Delta V_{ij} = abs(V_i - V_j) - C_i - C_j$$

Where ΔV_{ij} is the difference between the two measured average breakdown voltages, V_i is the average breakdown voltage for cable i, V_j is the average breakdown voltage for cable j, C_i is the 95.4% confidence interval for cable i, and C_j is the 95.4% confidence interval for cable j. If ΔV_{ij} is larger than zero, there is no overlap between the two measured average breakdown voltages, in other words, the two insulations have different breakdown voltages. Table 8 shows the calculated results for the white insulation of five different NM cables.

Table 8 - Differences in white insulation breakdown voltage

white	A	B	C	D	E
A		0.73 kV	-0.24 kV	0.01 kV	2.40 kV
B	0.73 kV		1.33 kV	1.58 kV	3.97 kV
C	-0.24 kV	1.33 kV		-0.59 kV	1.80 kV
D	0.01 kV	1.58 kV	-0.59 kV		1.71 kV
E	2.40 kV	3.97 kV	1.80 kV	1.71 kV	

The numbers in Table 8 are the differences between the measured average breakdown voltages with 95% confidence level for white insulation. For instance, the value in the cell at column A and row B shows that the breakdown voltage difference between Cable A and Cable B white insulation is 0.73 kV with a confidence level of 95%. Since the average breakdown voltage difference is greater than zero, Cable A and Cable B white insulation may be considered to be statistically different. On the other hand, the difference of the breakdown voltage between white insulation from Cable A and Cable C is minus 0.24

kV. Since this is less than zero, there is no statistical difference between the breakdown voltages of Cable A and C insulation materials.

The influence of the PVC plasticizer on breakdown voltages can be seen in Table 9, showing that the insulation breakdown voltage using trimellitate as plasticizer had a statistically higher breakdown voltage versus phthalate plasticizer.

Table 9 – Influence of PVC Plasticizer on Breakdown Voltage

NM Cable Insulation	Breakdown Voltage	Plasticizer
Cable A white	20.10 kV	Phthalate
Cable A black	17.10 kV	Phthalate
Cable B white	18.57 kV	Phthalate
Cable B black	19.36 kV	Phthalate
Cable C white	20.70 kV	Trimellitate
Cable C black	20.95 kV	Trimellitate
Cable D white	20.87 kV	Trimellitate
Cable D black	21.93 kV	Trimellitate
Cable E white	23.34 kV	Trimellitate
Cable E black	22.54 kV	Trimellitate

NM Cable Selection for Investigation of Damage and Degradation

According to the chemical composition analysis and electrical test data, the five types of NM cables can be categorized into two groups. Based on TGA data, the plasticizer used in the insulation, and the breakdown voltage, two cables, B and E, with distinct properties were selected for further investigation of the influence of installation damage and thermal degradation on dielectric strength. The characteristics of the selected cables are summarized in Table 10.

Table 10 - Cable B and Cable E characteristics

TGA results	Cable B	Cable E
Thermal decomposition rate peaks		
White Insulation (TGA test result)	321 °C; 478 °C	294 °C; 330 °C; 472 °C
Black insulation (TGA test result)	330 °C; 474 °C	295 °C; 333 °C; 477 °C
Insulation Plasticizer (FT-IR test result)	Phthalate	Trimellitate
Lead additive (EDS test result)	No	Yes
Dielectric breakdown voltage (kV)	18.97	22.94

Task 3 — Assessment of NM Cable Installation Damage

Electrical code inspection organizations record a significant number of NM cable installation Code violations every year[22], for the purpose of addressing improper installation issues and to improve installation practices. To better understand potential damage to the NM cable qualitatively as well as quantitatively, cables were installed using NEMA guidelines.

A series of scoping tests were conducting using common installation methods to assess the nature and degree of possible damage to NM cable insulation. Cable segments were installed on wood studs using NEMA the guidelines for installing the cables.

Figure 19 - NM cables installed on wood studs

Based upon field inspection reports[23], three types of damage scenarios were considered: (*a*) misaligned staple; (*b*) over-driven staple; and (*c*) inadvertent hammer impact to the NM cable jacket. The staples were driven into the wood studs using either a manual stapler; an electric stapler; or a hammer. At least 100 staples were used with each installation method. A typical installation of the NM cables is illustrated in Figure 19. The test results from staple puncture, over-driven staple, and hammer impact are described in the following sections.

Staple Puncture

When installing NM cable with a hammer, it was observed that the user has to tap the staple into the wood frame before hitting it hard and securing it. Therefore, it is unlikely to have staple puncture damage when using a hammer to install the NM cable. However, when installing NM cable with a staple gun, the view of the NM cable can be blocked to the installer by the staple gun. In this case, the staple gun may be misaligned with the NM cable and the staple may damage the conductor insulation. Figure 20 shows a picture of a misaligned staple and the conductor insulation damaged by the staple.

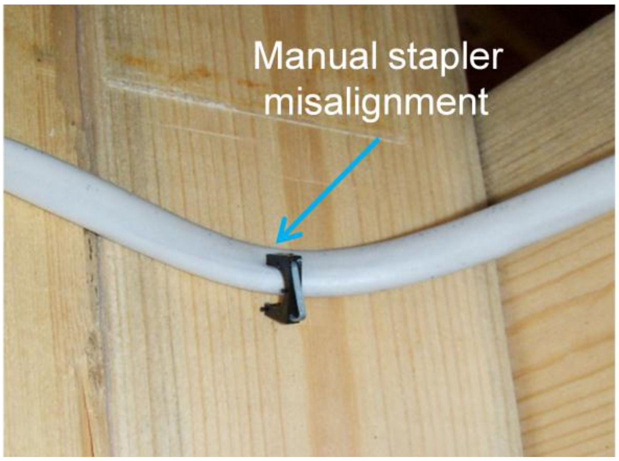


Figure 20 - NM cable damaged by misaligned staple

To estimate the potential for staple misalignment, using a stapler, and damage to the NM cable, 350 feet of NM cable was installed in a simulated attic space with 452 staples. The distance between the adjacent two staples is less than the maximum distance recommended by the NEMA NM cable installation guideline. After installation, the cable segments around the stapes with visible damage to the jacket were further examined for damage to the insulation. These segments were then tested for the breakdown voltage. The results are summarized in Table 11.

Table 11- NM cable staple misalignment damage

Installation method	Number of samples	Samples with visible jacket puncture	Samples with visible insulation puncture	Percentage of samples with insulation puncture
Electric stapler	136	22	5	3.7%
Manual stapler	207	5	1	0.5%

The result in Table 11 indicates that the manual stapler is less likely to misalign with the NM cable. One reason for this may that the manual stapler used in this investigation had a notch to align with the staple, thus facilitating installation without having the staple in sight (Figure 21).

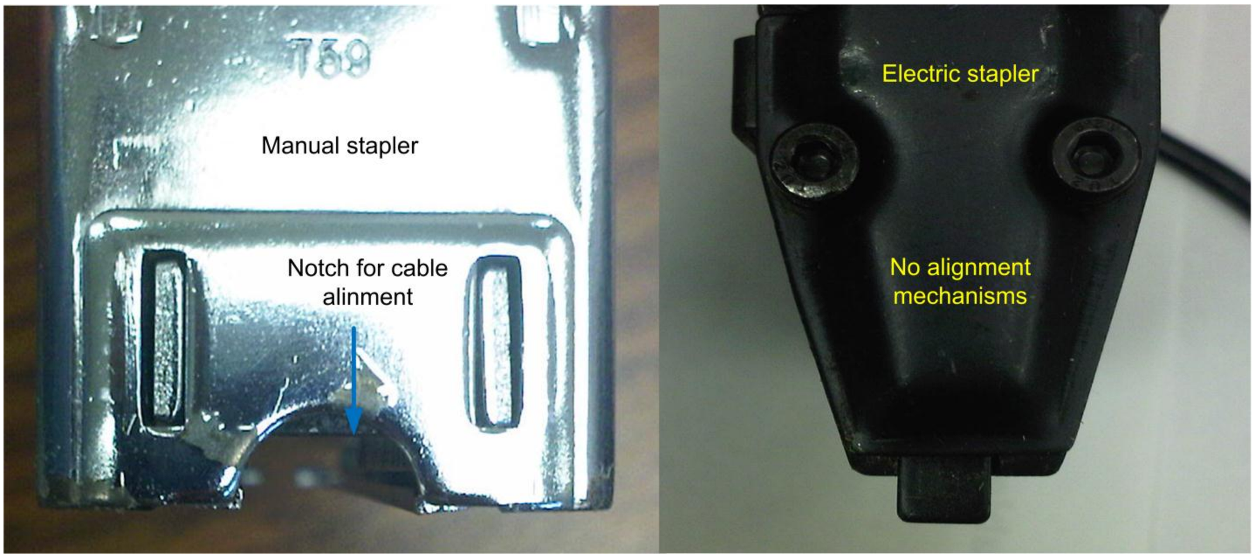


Figure 21 – Photograph of staplers with and without alignment notch

Overdriven Staple

During installation, a staple may be forced, over the NM cable jacket, into the wood stud to compress the jacket and insulation. It was observed that the degree of compression of the cable jacket by a staple is influenced by the type of staple used. Figure 22 compares the cross section of uncompressed NM cable with that of NM cable compressed by a staple with plastic insulation; and while Figure 23 compares the cross section of uncompressed NM cable with that compressed by a metal staple. Figure 22 shows that the staple with plastic insulation may act to protect the NM cable from being over-compressed.

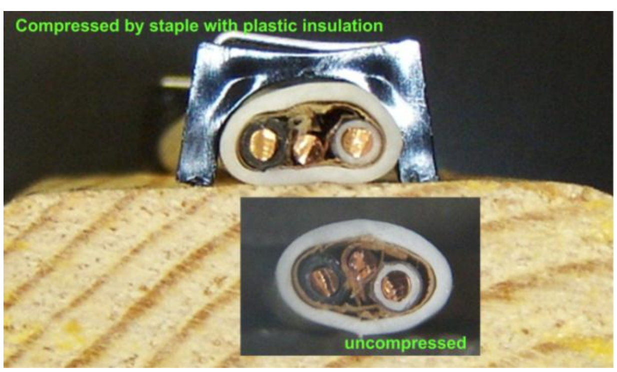


Figure 22 - NM cable compressed by a staple with plastic insulation

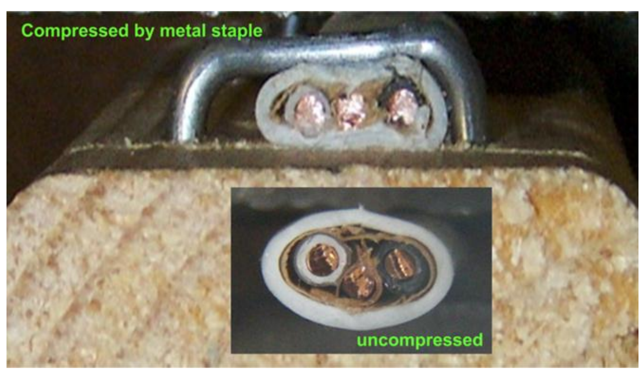


Figure 23 - NM cable compressed by a metal staple

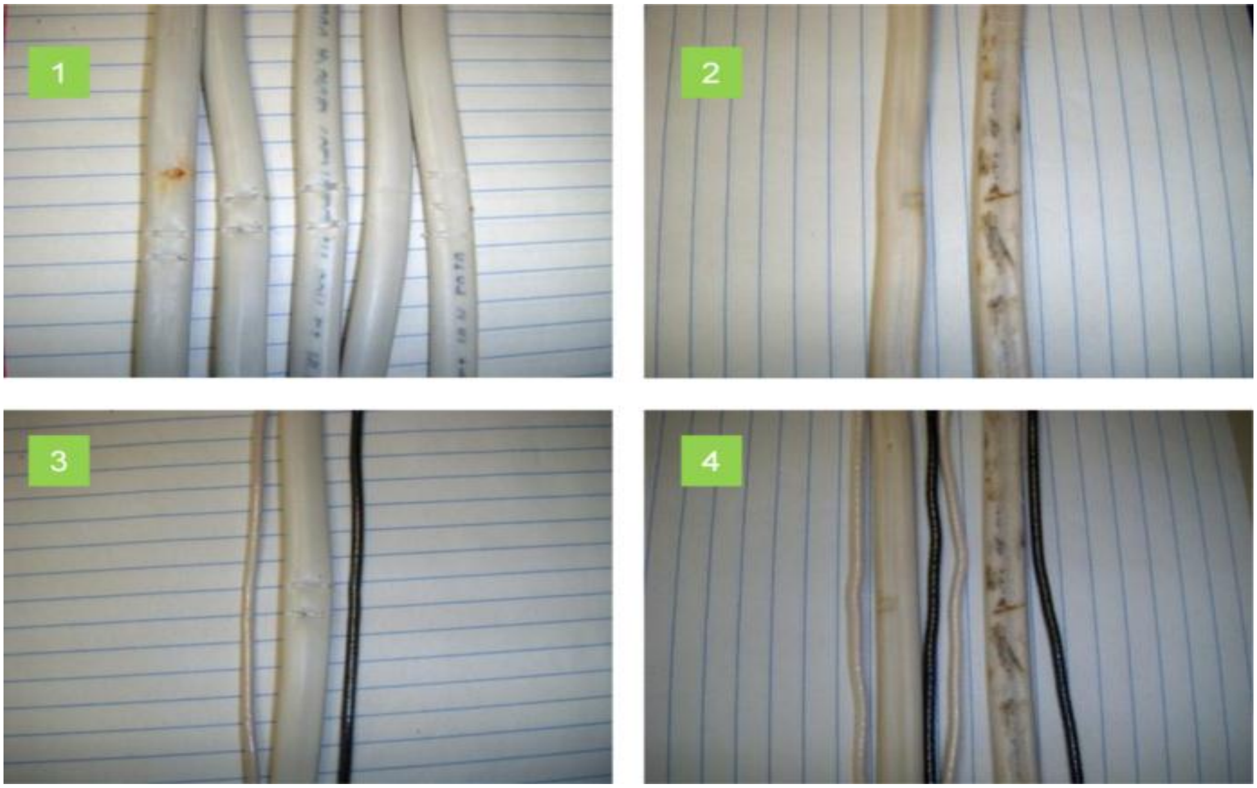


Figure 24 - Overdriven NM cable samples

Figure 24 depicts damage to NM insulation jackets by overdriven staples using various methods. Picture 1 shows NM cable damaged by staples overdriven by an electric stapler. Picture 2 shows NM cable samples damaged by staples overdriven with a hammer. Picture 3 shows exposure of conductor from a staple overdriven by an electric stapler. Picture 4 shows exposure of conductor from staples overdriven by a hammer. The visual inspection of the conductor insulation reveals that installation damage sometimes may generate visible damage to the jacket, but the same impact may not always generate visible damage on the conductor insulation.

To quantify the damage due to overdriven staples, the insulation breakdown voltage of the overdriven NM cable samples were measured as summarized in table 12.

Table 12 - Breakdown voltage of overdriven NM cable samples for cable E

Installation method	Compression mark	Number of damaged samples	Breakdown voltage (kV)	Number of samples with breakdown voltage less than 6 kV after damage
New	No	60	19.05 to 22.91	0
Manual stapler	No	10	19.3 to 21.8	0
Hammer	Yes	2	16.3 to 20.1	0
Electric stapler	Yes	11	10.51 to 20.1	0

The data in table 12 indicate that the staples overdriven by the hammer and electric stapler can significantly reduce the breakdown voltage of the NM cable conductor insulation, but overdriven staples with plastic insulation may not degrade the breakdown voltage of NM cable insulation. Table 12 also shows that all the overdriven samples passed the 6 kV breakdown voltage threshold, but had shown reduction in breakdown voltage from the undamaged values. Though initial damage from overdriven stapes was not expected to pose a serious issue with respect to breakdown voltage, this project also investigated whether breakdown voltage degraded further when overdriven NM cables were aged. This is discussed in Task 5.

Hammer Impact Damage

Since hammer is a common tool used to install NM cables, the potential for damage from this common practice was assessed. The depth to which the staple may be driven with a hammer into a wood stud was first characterized using a 16 oz. hammer with a head of 1 inch in diameter. The staple was 0.5 inches in height. Tests were conducted with one type of NM cable (Cable E) to measure the depth to which a metal staple is driven into the wood stud. In each case, two hammer blows were used to drive the staple into the wood stud. An illustration of the measurement is shown in Figure 25.

The measurements of the staple height, *d*, are presented in Table 13. The results were used to design a mechanical hammer simulator that provided a repeatable staple driving capability. The data indicate that the average distance between the top of the installed staple to the wood frame is 0.30 in. and the distribution is normal as shown in Figure 26.

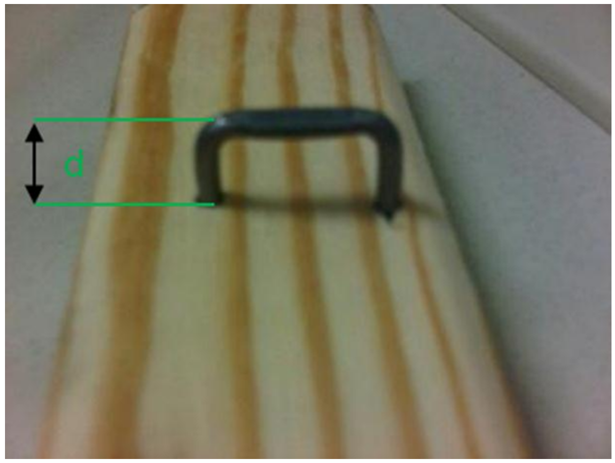


Figure 25 – Illustration of staple depth by hammer blows

Table 13 - NM cable installation by hammer and metal staples

Number of samples	Average distance from the top of the staple to the wood frame surface when NM cable is not compressed Ct (mm/in)	Average distance from the top of the staple to the wood frame surface d (mm/in)	Standard deviation (mm/in)
119	6.95/0.27	7.62/0.3	1.78/0.07

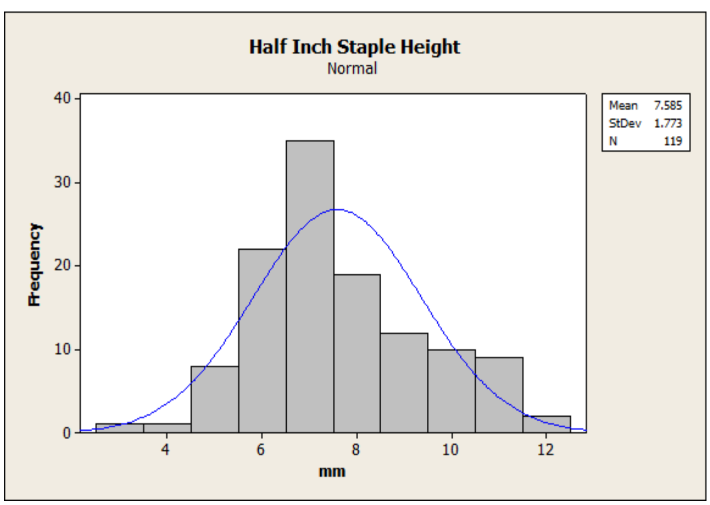


Figure 26 - Distribution of the distance between the top of the installed staple to the wood frame.

Hammer Impact Simulator Parameters

A hammer simulator shown in Figure 27 is designed for this project to test NM cable damage due to hammer hit. The hammer simulator consists of a metal base, adjustable arm, an electromagnet, and a power supply. Adjusting the height of the adjustable arm, or changing the weight of the hammer head allows for the application of different amounts of force to the NM cable samples under the test.

The following procedure was used to develop the drop height for the hammer head to simulate a repeatable staple driving depth of 0.30 inches with two or three drops.

1. Tap a metal staple on construction grade wood frame lumber and place it under the hammer of the hammer simulator as shown in Figure 27.
2. Set the hammer head at an initial height (*e.g.*, 3 ft.).
3. Release the hammer head.
4. Energize the electromagnet and set the hammer head.
5. Reposition the staple under the hammer head.
6. Release the hammer head.
7. Measure the distance between the top of the staple to the wood frame.
8. If the distance is less than 0.3 inches, reduce height of the hammer drop. If the distance is greater than 0.3 inches, increase the height of the hammer drop.
9. Repeat step 1 to step 8 until a staple depth of 0.3 inches is obtained with two hammer blows.

With this procedure, it was found that a 7ft-lb force would provide the required staple depth with two hammer drops; and a 5 ft-lb force would result in the required depth in three hammer blows.

Figure 27 - Hammer impact simulator

Breakdown Voltage Distribution of Hammer Impact Damaged NM Cable

The selected cables (Cable B and Cable E) were subjected to direct hammer blows using the hammer impact apparatus, which allows the ability to apply repeatable force to the cable jacket. The test cable was placed below the apparatus head as shown in Figure 27. The height of the head was adjusted to provide either 5 ft-lb or 7 ft-lb impact onto the test cable.

The hammer impact apparatus was released to provide a direct hit on the cable outer jacket. The black and white insulations within the cable were labeled and electrical breakdown tests were conducted on both the insulations. Figure 28 shows the procedure used. A total of 30 tests were conducted for each of the selected cables.

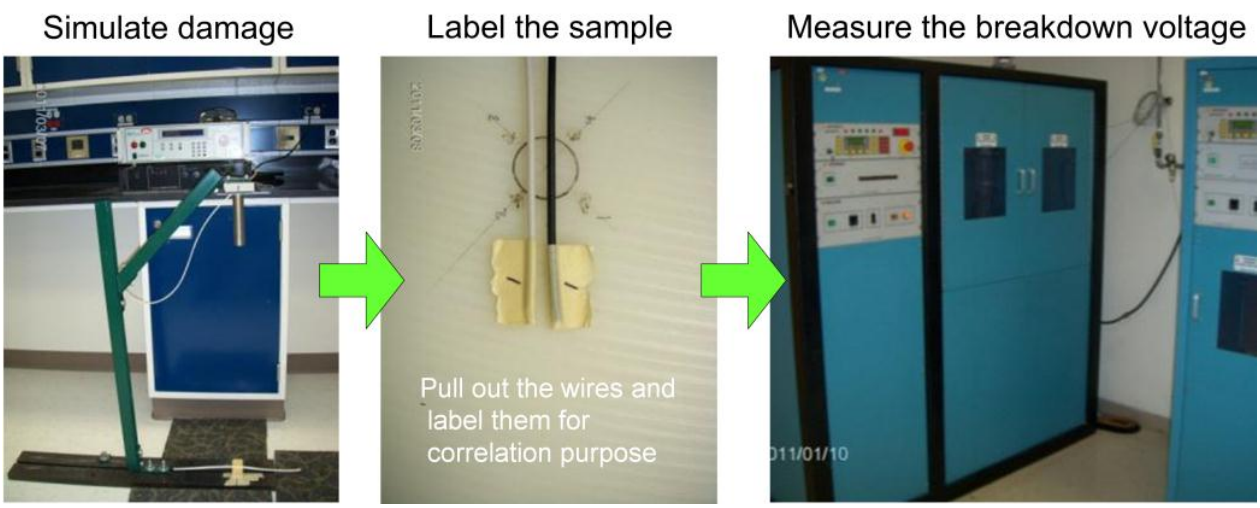


Figure 28 - Step-by-step procedure for damage to NM cable through direct hammer hit

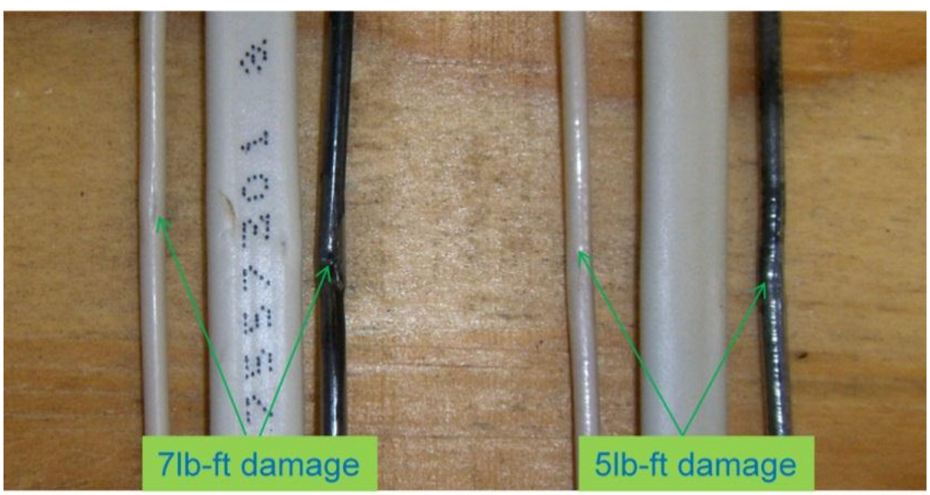


Figure 29 - Comparison of 7ft-lb and 5ft-lb damaged NM cable samples

Figure 29 compares the NM cable samples damaged by 7 ft-lb and 5 ft-lb hammer drops. Figure 29 shows that the 7 ft-lb hammer impact is visible, while the 5 ft-lb hammer impact creates damage that is difficult to detect visually. The hammer impact damage to both the black and the white conductor in the same piece of the NM cable sample was characterized though breakdown voltage tests of both the black and white conductors. The electrical breakdown voltages for Cable E are shown in Figure 30.

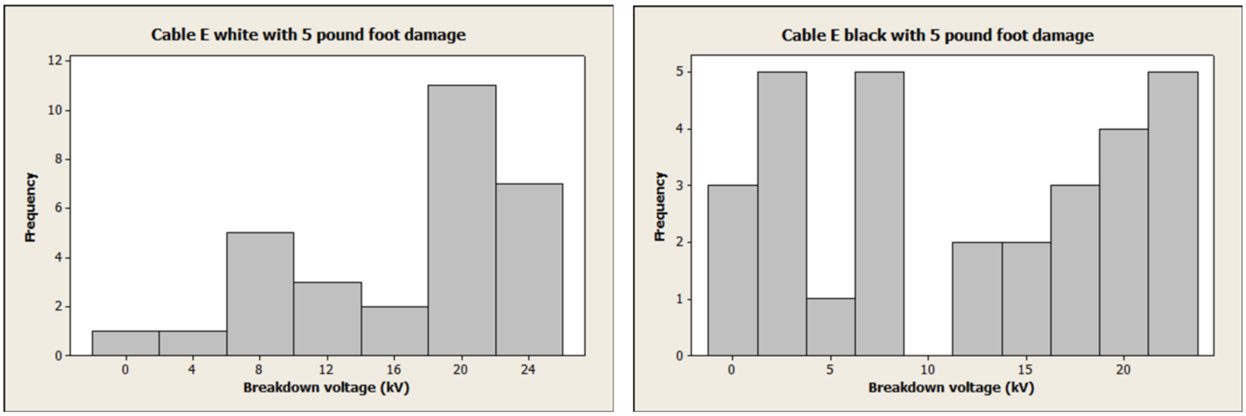


Figure 30 - Breakdown voltage distribution of hammer-damaged NM cable insulation

The breakdown voltages for the white and black insulation were combined to provide an assessment for the whole cable. This is presented, as an example, for Cable E for data with 5 ft-lb hammer drop in Figure 31.

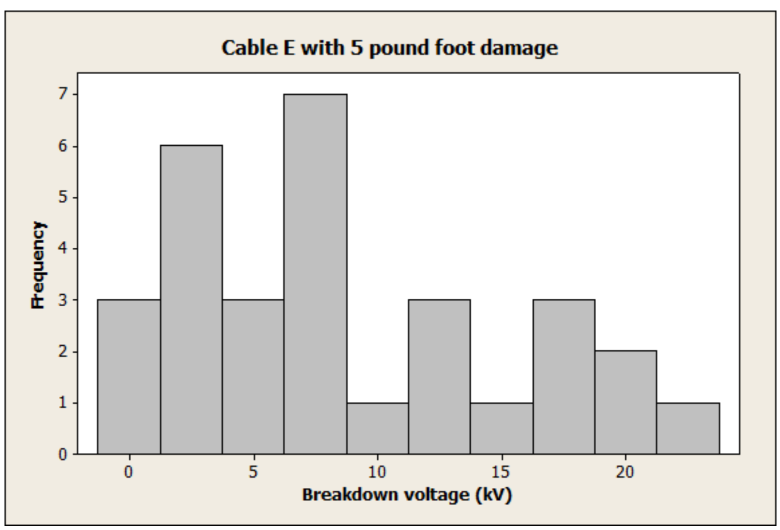
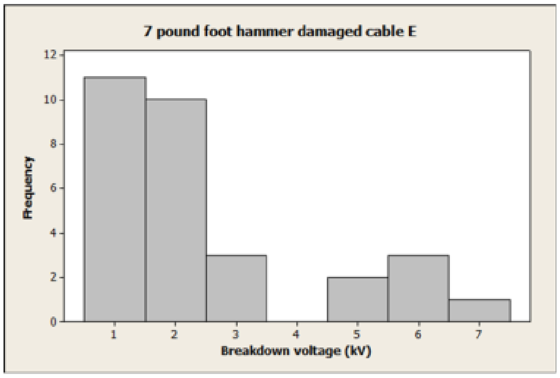


Figure 31 - Breakdown voltage distribution for combined black and white insulation (Example using Cable E data from a 5 ft-lb hammer blow)

The combined (black and white insulation) breakdown insulation data for all 30 replicates of each sample, and for 5 and 7 ft-lb hammer drops are shown in Figure 32 and Figure 33. The data in Table 14 show that a hammer impact can result in the NM cable insulation dielectric strength to fall well below the 6 kV threshold value. In some cases, the 7 ft-lb hammer impact cracked the NM cable insulation, an example of this is shown in figure 34.



More than 90% of cable E samples with 7 pound foot hammer damage failed 6kV breakdown voltage test.

About 37% of cable E samples with 5 pound foot hammer damage failed 6kV breakdown voltage test.

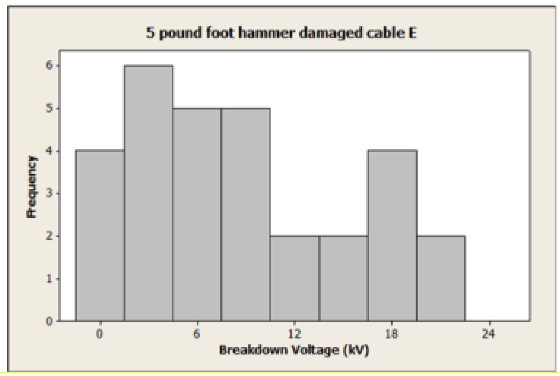
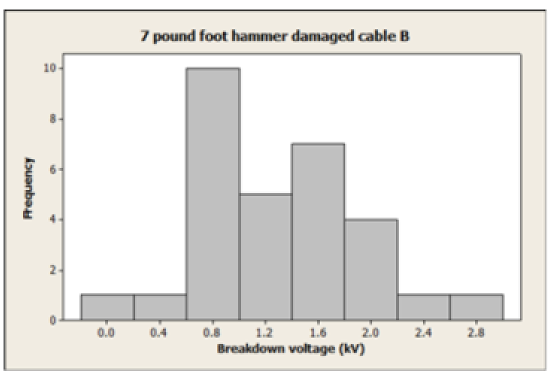


Figure 32 - Breakdown voltage distribution of cable E damaged by hammer impact



100% of cable B samples with 7 pound foot hammer damage failed 6kV breakdown voltage test

100% of cable B samples with 5 pound foot hammer damage failed 6kV breakdown voltage test

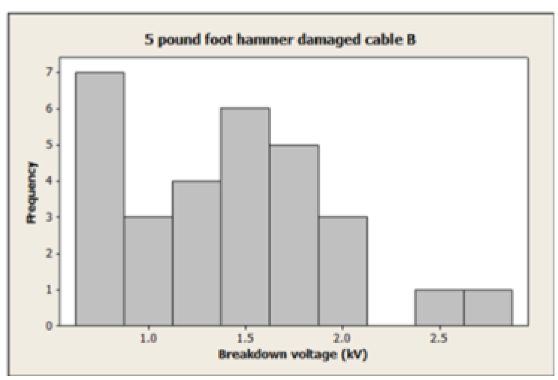


Figure 33 - Breakdown voltage distribution of cable B damaged by hammer impact

Table 14 provides a summary the average breakdown voltages, from 30 replicates for each cable and hammer ft-lb values.

Table 14 - Breakdown voltage of hammer-damaged NM cable (measurement of the damaged portion)

Sample	Minimum breakdown voltage (kV)	Average breakdown voltage (kV)	Maximum breakdown voltage (kV)	% of samples below 6kV
Cable B 5ft-lb	0.71	1.40	2.70	100
Cable B 7ft-lb	0.13	1.25	2.68	100
Cable E 5ft-lb	0.08	8.79	21.38	37
Cable E 7ft-lb	0.64	2.42	6.89	93

Figure 34 - NM Cable insulation cracked by 7ft-lb hammer impact

Summary of Damage to NM Cable from Common Installation Practices

The findings of damage from common installation practices of the NM cable may be summarized as follows:

- Misalignment is an issue when installing NM cable with a stapler. The misaligned staple may puncture the conductor insulation. Once punctured, the insulation breakdown voltage reduces to the level of an air gap comparable with the insulation thickness, which can be much lower than 1 kV (0.3 mm gap with a dielectric strength of air of 3 MV/m, which is approximately 900V).[24,25,37]

- Overdriving a staple reduces the NM cable insulation breakdown voltage, but the dielectric breakdown voltage was still above 6 kV for both types of NM cables under the test.
- Typical hammer impact force during typical installation is estimated to vary from 5 ft-lb to 7 ft-lb.
- Damage from a direct hammer impact to the cable jacket during installation may significantly reduce the breakdown voltage of the insulation materials.

Task 4 — Assessment of NM Cable Degradation

Introduction

Over the service life, the NM cable may be exposed to a range of temperature and humidity conditions, with the insulation materials degrading with time (*i.e*., age). This variation in insulation composition is expected to change the dielectric breakdown voltage of the cable. If the insulation breakdown voltage falls below 6 kV, the increased frequency of voltage surges occurring at these lower magnitudes (see Figure 3) may lead to an accelerated rate of carbonization of the insulation material, and therefore increased potential for ignition from arcing. The insulation aging involves both chemical and physical processes whose rates are correlated to the surrounding temperature. The insulation materials from all the selected NM cables were found to be plasticized PVC-based compounds with a co-extruded nylon protective layer. The PVC-based insulation has several components (*e.g*., plasticizer, thermal stabilizer) to provide the appropriate mechanical and processing properties. The main aging mechanism that may lead to insulation embrittlement and reduction of breakdown voltage is anticipated to be the loss of plasticizer as this is typically present in PVC compounds in the range of 15 to 40%.

To study the effect of aging on materials, it is desirable to accelerate the aging process. A common approach to achieve this is to assume that thermal aging follows Arrhenius type rate processes,[26] where a faster degradation rate may be achieved by increasing the exposure temperature. However, based upon the polymer chemistry there is a practical upper limit of the temperature that may be utilized without altering the degradation mechanism. Literature on compounded PVC degradation[27] suggests that dehydrochlorination may start at temperatures exceeding 150°C, a temperature which is not expected to be reached in real-world applications and therefore would result in aging data that is not representative of natural aging. Thus, to investigate the rate of loss of the plasticizer and the consequent reduction in electrical breakdown voltage, an upper limit of 150°C was selected.

Test Procedures

Controlled Temperature Exposure Tests

The test specimens were prepared for the controlled temperature exposure tests as follows: (i) samples of NM Cables B and E were cut into 18-inch long test specimens and the insulated conductors were separated from the outer cable jacket; (ii) a half-inch of the insulation was removed from each end, thus exposing the copper conductor, and the copper conductor was bent into a hook to facilitate post-exposure breakdown voltage testing. A total of 30 specimens of a particular cable type (either B or E) were loaded into the exposure chamber. Each test specimen was weighed prior to elevated temperature exposure, and the specimens were then looped and hung in a temperature-controlled chamber as shown in Figure 35. To understand the contamination from off-gassing from the insulation, the initial weight loss test had only one black conductor sample and one white conductor sample placed in the temperature controlled chamber at any time. Test specimens were removed at regular intervals, and reweighed to document weight loss with time. The comparison of weight loss data indicates that there is no measurable weight loss difference when aging small number of samples in the chamber and aging large number of samples in the chamber.

Figure 35 - Black and white NM cable conductors in the test chamber for thermal aging

Accelerated Aging Insulation Weight Loss

The results from the accelerated aging and the subsequent breakdown voltage tests for the cable insulation materials are presented herein. Table 15 the weight loss data for Cable B wire insulation. The normalized weight was calculated as the weight ratio of the aged wire insulation to the original wire insulation. The data in the table shows that the normalized weight decreases over the time.

Table 15 – Example of 150 ^{o}C weight loss data for Cable B insulation with nylon layer, showing exposure time and the normalized weight for white and black insulation materials.

Time (days)	sample	original insulation (g)		aged insulation (g)		normalized weight	
		white	Black	white	black	white	black
0.02	1	1.787	2.127	1.777	2.110	0.9944	0.9920
	2	1.827	1.963	1.815	1.948	0.9934	0.9924
	3	1.769	2.069	1.76	2.053	0.9949	0.9923
0.04	1	1.869	1.901	1.857	1.885	0.9936	0.9916
	2	1.742	1.926	1.730	1.908	0.9931	0.9907
	3	1.958	1.939	1.946	1.922	0.9939	0.9912
0.29	1	1.702	2.015	1.691	1.998	0.9935	0.9916
	2	2.043	2.136	2.026	2.112	0.9917	0.9888
	3	1.870	1.853	1.852	1.831	0.9904	0.9881
1	1	1.750	1.898	1.726	1.872	0.9863	0.9863
	2	1.934	1.848	1.913	1.822	0.9891	0.9859
	3	1.974	1.92	1.952	1.898	0.9889	0.9885
2	1	1.901	2.12	1.875	2.085	0.9863	0.9835
	2	1.781	1.906	1.756	1.876	0.9859	0.9842
	3	1.749	2.036	1.732	2.002	0.9903	0.9833
3.25	1	1.996	2.085	1.967	2.038	0.9855	0.9775
	2	1.612	1.858	1.588	1.824	0.9851	0.9817
	3	1.710	1.899	1.684	1.863	0.9848	0.9810
5	1	1.836	1.926	1.804	1.883	0.9826	0.9777
	2	1.799	1.938	1.769	1.892	0.9833	0.9763
	3	1.787	2.226	1.754	2.176	0.9815	0.9775
7	1	1.794	2.003	1.755	1.937	0.9783	0.9670
	2	1.826	1.891	1.785	1.831	0.9775	0.9683
	3	1.979	1.997	1.934	1.933	0.9773	0.9679

For the measurement of insulation weight loss with the nylon layer, the sample preparation and measurement procedure are the same as that for the insulation without the nylon, except aging the NM cable insulation samples with the nylon intact. Figure 36 compares the measured weight loss of Cable B insulation with and without the nylon layer. The result shows that the nylon significantly retards weight loss.

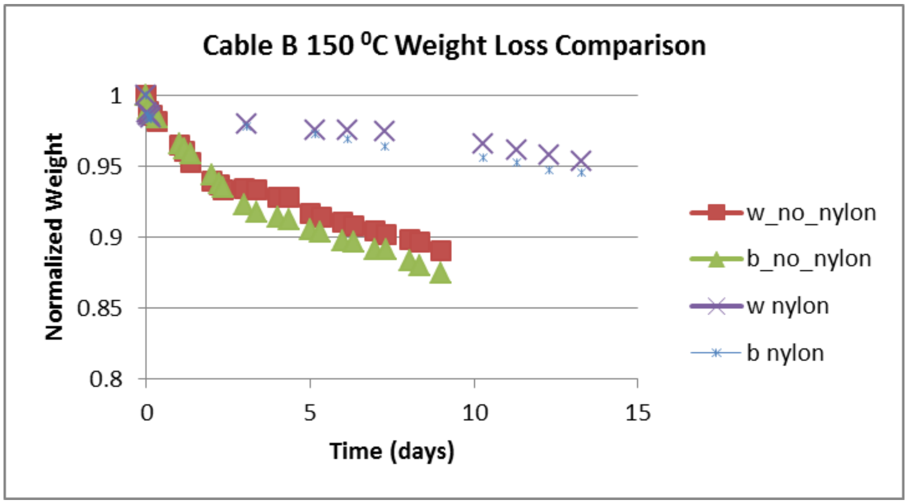


Figure 36 Comparison of Cable B insulation aging with and without nylon layer

Figure **37** shows a similar result for Cable E. The data indicate that the insulation weight loss occurs approximately twice as fast when the nylon coat is removed compared to when it is present.

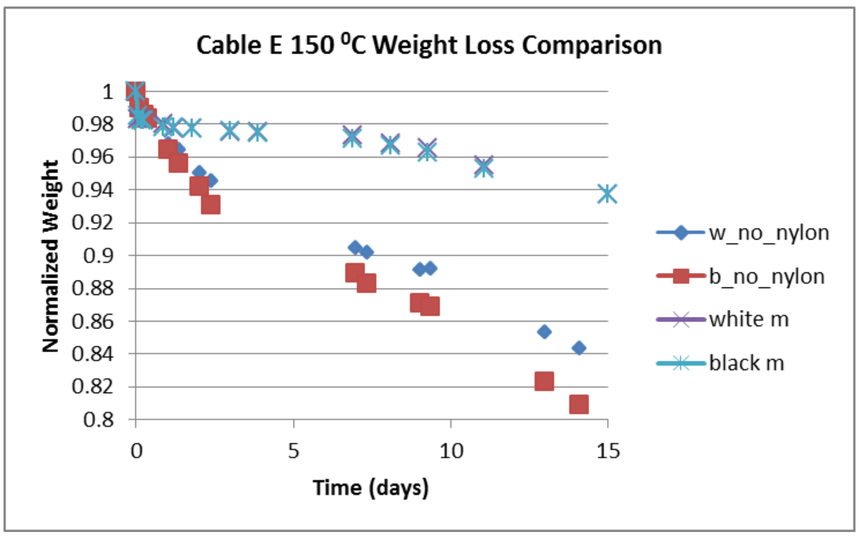


Figure 37– Comparison of Cable E insulation aging with and without nylon layer

Insulation Weight Loss under Different Temperatures

Because the insulation weight loss rates are different at different temperatures, weight loss data were obtained at different temperatures. Figure 38 shows the Cable B normalized weight loss at 120°C, 135°C and 150°C. Figure 39 shows the Cable E normalized weight loss at 120°C, 135°C and 150°C. The data indicate that the Cable B weight loss rates at 150°C starts accelerating after about three days of aging, while Cable E weight loss at 150°C starts accelerating after about seven days of aging. Cable B also has higher weight loss rate than Cable E at 120°C and 135°C.

Based on the NM cable insulation chemical composition analysis in Section 4, the lower weight loss rate of Cable E may correlate to the trimellitate plasticizer, while the higher weight loss rate of Cable B may correlate to the phthalate plasticizer.

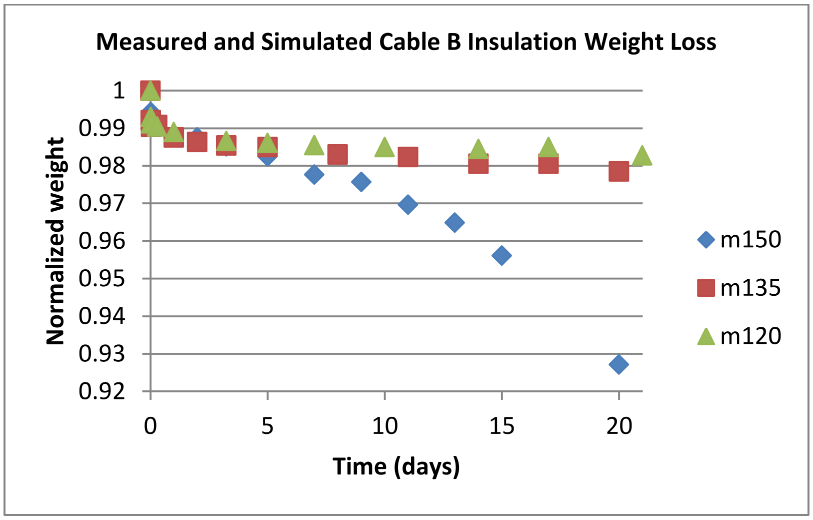


Figure 38 – Cable B insulation weight loss under different temperatures. m150 is the data at 150°C, m135 is the data at 135°C, and m120 is the data at 120°C.

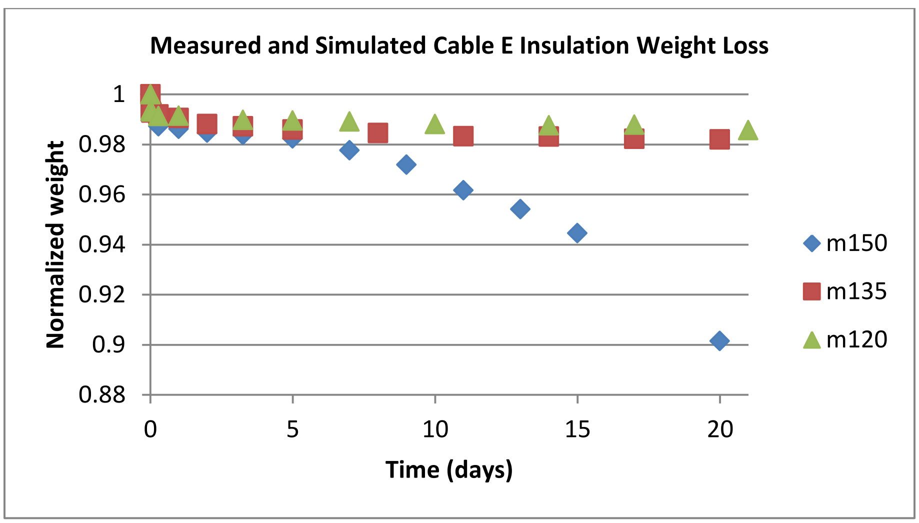


Figure 39 – Cable E insulation weight loss under different temperatures. m150 is the data at 150°C, m135 is the data at 135°C, and m120 is the data at 120°C.

Insulation Weight Loss and the Breakdown Voltage

The aged cable samples were tested for dielectric breakdown voltage to establish a correlation of dielectric breakdown and insulation weight loss. Table 17 and Table 16 show the weight loss data for Cable B and Cable E (with nylon layer), respectively.

Table 17 – Weight loss data for Cable B insulation with nylon layer, showing exposure time, the normalized weight and the corresponding breakdown voltage.

Cable B 150 ^{0}C	Breakdown Voltage (kV)		Normalized Weight		Average Normalized Weight		Average Breakdown Voltage (kV)	
time	white	black	white	black	white	black	white	black
0					1	1	18.6	19.4
0.02 days	23.34	23.52	0.9944	0.9920	0.9942	0.9922	24.3	24.4
	25.08	24.65	0.9934	0.9924				
	24.61	24.93	0.9949	0.9923				
0.04 days	23.18	24.21	0.9936	0.9916	0.9935	0.9912	24.0	25.5
	23.84	25.06	0.9931	0.9907				
	25.06	27.1	0.9939	0.9912				
0.29 days	24.55	26.51	0.9935	0.9916	0.9919	0.9895	25.6	23.5
	26.14	22.81	0.9917	0.9888				
	26.2	21.08	0.9904	0.9881				
1.00 days	21.48	25.85	0.9863	0.9863	0.9881	0.9869	22.7	24.1
	23.55	23.31	0.9891	0.9859				
	23.04	23.07	0.9889	0.9885				
2.00 days	24.61	20.5	0.9863	0.9835	0.9875	0.9837	22.4	19.9
	20.48	19.34	0.9860	0.9843				
	22.04	19.81	0.9903	0.9833				
3.25 days	24.34	23.04	0.9855	0.9775	0.9851	0.9801	23.1	21.3
	22.25	19.89	0.9851	0.9817				
	22.78	21.06	0.9848	0.9810				
5.00 days	21.91	22.14	0.9826	0.9777	0.9825	0.9772	22.1	21.4
	21.56	19.97	0.9833	0.9763				
	22.73	22.14	0.9815	0.9775				
7.00 days	23.76	22.54	0.9783	0.9670	0.9777	0.9678	21.9	17.2
	21.96	17.72	0.9775	0.9683				
	20.1	11.42	0.9773	0.9680				
9.00 days	22.04	18.67	0.9738	0.9601	0.9757	0.9615	22.5	19.3
	22.28	18.14	0.9745	0.9622				
	23.1	21.01	0.9789	0.9621				
11.00 days	21.46	17.93	0.9706	0.9528	0.9697	0.9533	20.6	18.6
	18.91	19.02	0.9688	0.9524				
	21.51	18.99	0.9696	0.9547				
13.00 days	18.52	19.68	0.9644	0.9511	0.9649	0.9491	18.9	18.7
	17.96	18.22	0.9652	0.9478				
	20.1	18.25	0.9650	0.9483				
15.00 days	19.89	16.58	0.9564	0.9439	0.9561	0.9439	18.1	17.0

Table 18 – Weight loss data for Cable E insulation with nylon layer, showing exposure time, the normalized weight and the corresponding breakdown voltage.

Cable E 150 ^{0}C	Breakdown Voltage (kV)		Normalized Weight		Average Normalized Weight		Average Breakdown Voltage (kV)	
time	white	black	white	black	white	black	white	black
0					1	1	23.3	22.5
0.02 days	28.82	26.06	0.9934	0.9938	0.9935	0.9935	25.5	26.7
	19.73	25.27	0.9943	0.9931				
	27.97	28.69	0.9927	0.9935				
0.04 days	26.38	24.48	0.9924	0.9920	0.9923	0.9923	26.4	26.3
	26.38	28.77	0.9917	0.9927				
	26.46	25.64	0.9927	0.9923				
0.21 days	27.2	27.2	0.9869	0.9904	0.9872	0.9872	26.9	26.4
	27.36	27.92	0.9870	0.9877				
	26.22	23.97	0.9878	0.9833				
1.00 days	25.98	27.81	0.9884	0.9852	0.9862	0.9870	26.5	26.4
	26.28	27.52	0.9864	0.9890				
	27.31	23.95	0.9837	0.9870				
2.00 days	21.14	24.66	0.9846	0.9834	0.9847	0.9843	23.7	24.3
	23.71	24.45	0.9848	0.9839				
	26.20	23.92	0.9846	0.9858				
3.25 days	24.29	23.89	0.9825	0.9820	0.9837	0.9828	23.8	23.8
	21.40	21.75	0.9855	0.9827				
	25.59	25.69	0.9831	0.9837				
5.00 days	23.65	23.97	0.9823	0.9821	0.9823	0.9819	22.6	21.8
	23.71	22.57	0.9818	0.9822				
	20.45	18.89	0.9828	0.9814				
7.00 days	22.94	21.88	0.9775	0.9762	0.9777	0.9767	22.8	21.1
	21.53	20.13	0.9774	0.9776				
	23.95	21.30	0.9782	0.9762				
9.00 days	22.28	23.07	0.9725	0.9705	0.9718	0.9703	21.9	22.2
	21.61	23.20	0.9724	0.9704				
	21.91	20.29	0.9706	0.9700				
11.00 days	21.01	21.40	0.9625	0.9597	0.9616	0.9603	20.5	21.8
	18.70	22.12	0.9615	0.9603				
	21.67	21.77	0.9609	0.9609				
13.00 days	23.20	21.06	0.9542	0.9610	0.9540	0.9514	21.1	20.9
	19.92	21.75	0.9537	0.9524				
	20.24	19.97	0.9542	0.9407				
15.00 days	20.34	20.42	0.9442	0.9469	0.9445	0.9460	20.9	20.0
	21.91	19.5	0.9453	0.9453				
	20.53	20	0.9441	0.9460				

The influence of weight loss for NM cable B insulation from thermal aging on breakdown voltage is presented in Figure 40. The degradation data for cable E is under development and will be added to the final report shortly.

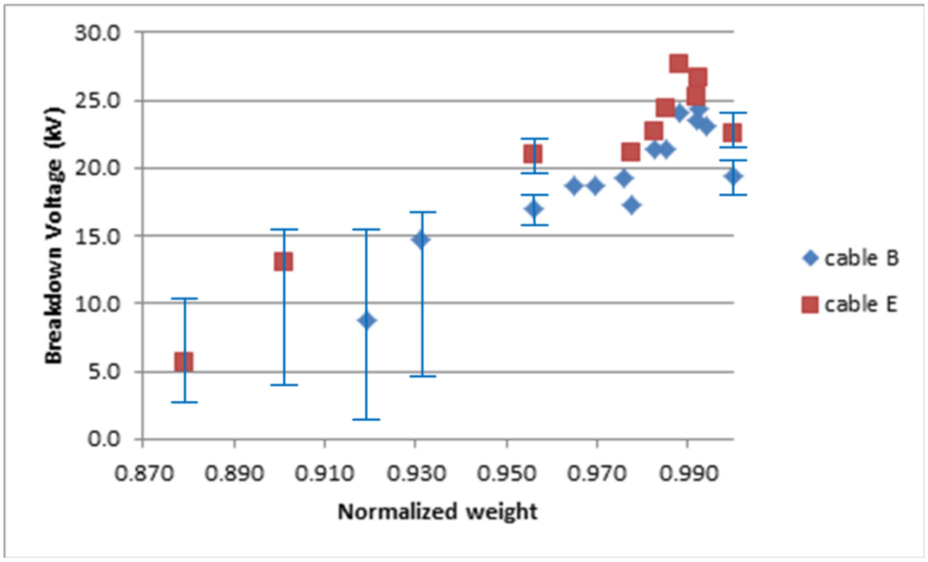


Figure 40 - Breakdown voltage and normalized insulation weight from samples aged at 120 ^{o}C, 135^{o}C and 150^{o}C. The error bars indicate the range of the test data.

The aged insulation breakdown voltage was initially seen to increase when the weight loss was less than 2%. But when the weight loss exceeded 4%, the aged insulation breakdown voltage trended lower. When the weight loss exceeds 8%, the aged insulation average breakdown voltage was less than 10kV. A breakdown voltage distribution for Cable B is depicted in Figure 41; and shows that 30% of the samples aged at 150 ^{0}C for 29 days have breakdown voltage less than 6kV.

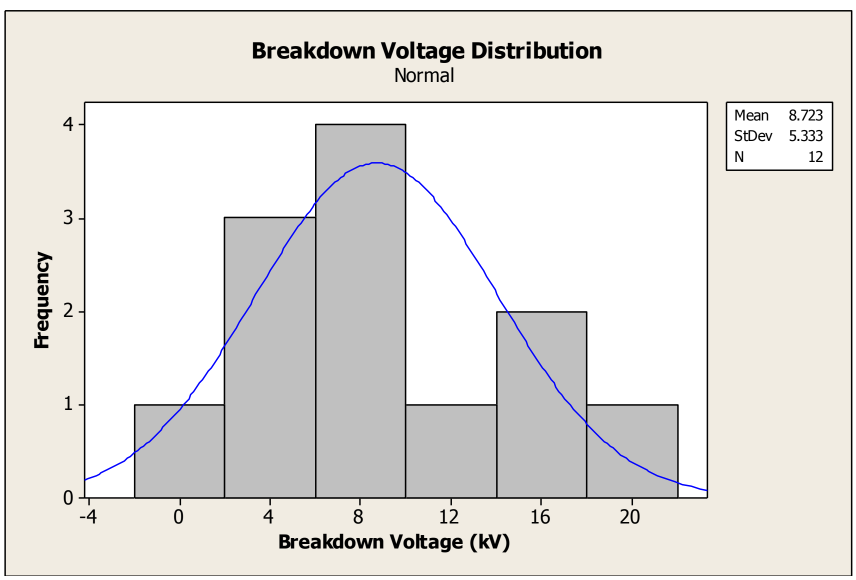


Figure 41 – Cable B insulation breakdown voltage distribution after aged at 150 ^{0}C for 29 days

Summary of Thermal Degradation of NM Cables

- Weight loss is found to be a good aging indicator, since weight loss occurs due to loss of PVC plasticizer.
- Weight loss rate increases with the temperature.
- Breakdown voltage of the NM cable conductor insulation initially increases with the loss of weight but then trends lower. The reason for this behavior is under the investigation for the final report.
- The nylon layer was found to retard the rate of weight loss for both cable B and cable E.

Task 5 — Assessment of Combined NM Cable Installation Damage and Aging Degradation

Task 3 discussed potential causes and consequences of NM cable damage during installation. The test results showed that hammer impact can result in immediate NM cable breakdown voltage failure, while over-compression may only reduce the NM cable breakdown voltage, instead of causing immediate failure of the NM cable. Because hammer impact results in NM cable failure without the need for an aging effect, this section focuses only on the thermal aging impact to the over-compressed NM cable.

Breakdown Voltage Measurement of the NM Cable with Jacket

Measuring the thermal aging impact to NM cable damaged through over-compression required the measurement of the breakdown voltage of the NM cable with its jacket intact. The challenge of testing the complete NM cable is that the corona formed at the test voltages above 3 kV may short the electrodes before insulation breakdown is achieved. To reduce the impact of the corona, a longer NM cable sample was used and the cable jacket opening was sealed with silicone based sealant. Figure 42 shows the prepared sample inside the chamber of the high-voltage tester.

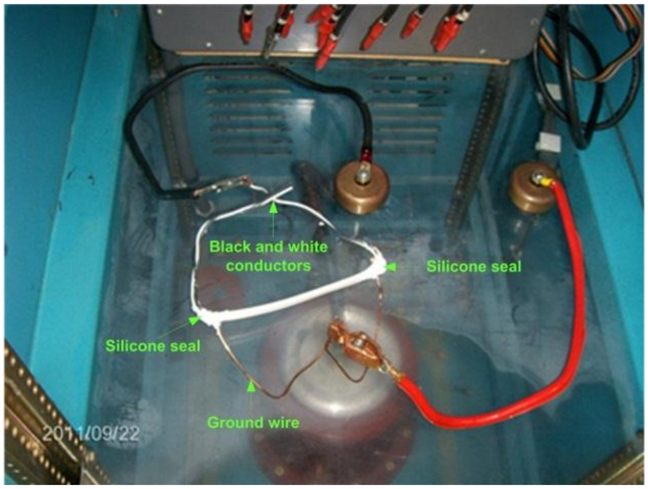


Figure 42 – Setup for the breakdown voltage test for intact NM Cable

Since most of the experiments conducted in this work use short segments of NM cable as test samples, and samples with relatively high breakdown voltage (*e.g.*, in excess of 15 kV), the effect of corona discharge required that breakdown voltage testing be conducted by testing the black and white conductors separately. As it was necessary to use intact cable to evaluate the effect of over-compression on breakdown voltage, and since corona discharge was found to still be an issue over 20 kV with the intact NM cable even after test modifications were made, it was possible to use only samples from Cable B for the test. This was because Cable B exhibited breakdown voltage values for undamaged, intact cable less than 20 kV. Samples from Cable E therefore were not evaluated for the influence of combined damage and degradation on dielectric breakdown voltage.

To check if the two different breakdown voltage test methods are consistent, or at least correlate, with one another, the breakdown voltage of 30 undamaged, intact NM Cable B samples were characterized and the results were compared with those from the breakdown voltage of the separated NM Cable B conductors. Table 19 is a comparison of Cable B breakdown voltages from the two different test methods. The result shows that the intact NM cable breakdown voltage is statistically identical to the single conductor.

Table 19 - Breakdown voltage comparison

Cable B with jacket	White conductor	Black conductor
19.1 ± 0.9kV	18.6 ± 1kV	19.4 ± 0.8kV

Test Sample Preparation and Test Results

Two sets of test specimens were prepared for this study. One set of samples were damaged through over-compression, the other set were subjected to both over-compression damage and subsequent thermal degradation.

The preparation of the over-compressed samples is as follows:

1. Cut the NM cable into two-foot long samples
2. Remove three quarters of the NM cable jacket from the sample
3. Tie the two ends of the ground wire together
4. Remove about one half-inch of insulation from the end of the black and the white conductors
5. Twist the black and white conductors together
6. Use the hammer simulator to staple the sample onto the wood stud
7. Measure the distance from the top of the staple to the top surface of the wood stud
8. Label the sample and record the measured distance between the top of the staple to the top surface of the stud
9. Seal the cable jacket openings with silicone

The procedure to prepare the over-compressed and thermally aged sample is the same as above, but the samples were then aged in the thermal chamber at a constant temperature using the same method as described in Task 4. Figure 43 shows a prepared over-compressed sample. Figure 44 shows a prepared over-compressed sample that was subsequently aged at 150°C for three days.

Figure 43 - Over-compressed NM cable B sample for breakdown test

Figure 44 - Over-compressed and thermally aged NM cable B sample for breakdown test

Table 20 - Comparison of new, aged, and over-compressed Cable B samples

	Cable with jacket	Over-compressed cable with jacket	Over-compressed and aged at 150°C for 3 days	Un-compressed and aged at 150°C for 3 days
Average breakdown voltage	19.1±0.9kV	18.6±0.5kV	12.7±7kV	20.7±1.2kV
Distance from the stud to the staple top	> 5.4 mm	4.44±0.44mm	4.80±0.27mm	N/A

To obtain statistically significant data, 30 samples were prepared for each of the four different sample conditions. Table 20 is a comparison of the measured results. The first row in Table 20 shows the breakdown voltages of different samples. The second row of Table 20 shows the distance from the top the staple to the top surface of the wood stud, which indicates how hard the NM cable is compressed. The staple distance measurements show that the over-compressed and aged cable samples were compressed by 0.6 mm, comparable with the intact cable samples, but not as severe as the over-compressed cable samples.

The data in Table 20 also show that the over-compressed and aged NM cable samples have significantly lower breakdown voltage compared with other samples, which indicates that the service life of the over-compressed NM cable can potentially be much shorter than the intact NM cable in a hot environment.

NM Cable Voltage Surge Test

The damage and degradation work conducted in this report demonstrates that the insulation breakdown voltage of NM cable can be significantly reduced, which increases the potential of formation of a carbonized path and arcing. However, this does not yet show the propensity of insulation breakdown to cause sufficient arcing to ignite the cable insulation. Therefore, to understand whether reduced breakdown voltages may lead to ignition of the damaged and aged NM cables, 100 hammer-damaged NM cable samples and 100 aged NM cable samples were tested per the UL1449 voltage surge standard. Figure 45 shows the samples prepared for voltage surge test. The hammer-damaged samples were prepared as follows:

- Samples were cut to a length of about 18 inches.
- The sample is secured to a piece of pinewood with two metal staples.
- A test fixture is used to damage the NM cable by dropping a two-pound steel hammer head on the test sample from a height of 3.5 ft. This is the same method described in the prior hammer impact studies.

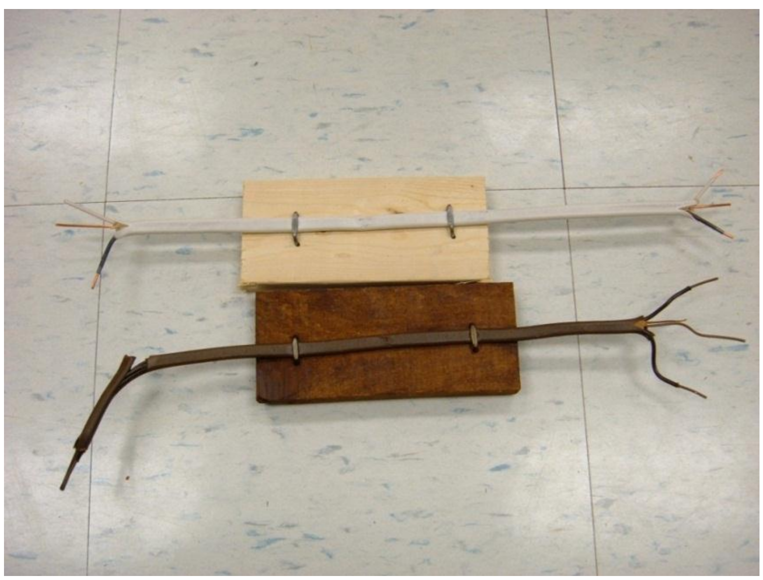


Figure 45 – Hammer-damaged and aged NM cable samples for the UL1449 test.

The test setup was as follows:

- Line and neutral of the tested samples were energized with 120VAC during the voltage surge.

- 6kV positive surge was applied from both line and neutral to ground, 1.2μs rise time, 50μs fall time, 500A, triggered at 120VAC phase angle of 90° (wave form in Figure 46).
- 6kV negative surge was applied from both line and neutral to ground, 1.2μs rise time, 50μs fall time, 500A, triggered at 120VAC phase angle of 270°.
- Each sample was tested with one positive 6kV surge and one negative 6kV surge.

The hammer-damaged NM cable samples exhibited arcing for nine of the 100 damaged samples during the tests. Because the electrical arcing was of a very short duration and generated little damage to the samples, the same 100 hammer damaged samples were placed into a temperature chamber and aged at 145°C (145 °C was used for the purpose to collect thermal aging data at an additional temperature point, in addition to the purpose of aging for the surge testing) for eight days. Figure 46 shows the schematic for the test and Table 21 summarizes the test results.

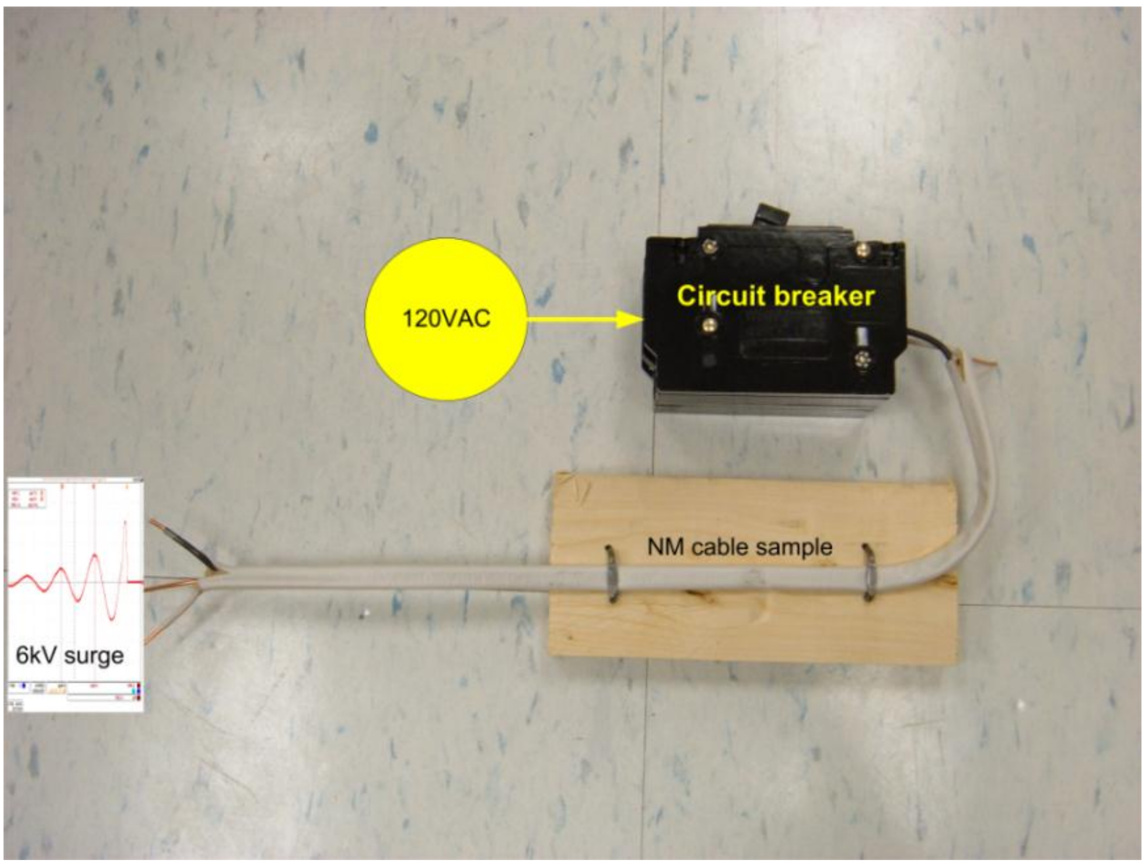


Figure 46 – NM cable voltage surge test schematic.

Table 21 – Summary of the UL1449 test results.

	Hammer damaged	Hammer damaged and aged
Total number of samples	100	100
Number of samples arced due to hammer damage	9	2
Number of samples arced due to over compression	0	0
Number of samples triggered 120VAC breaker	0	0
Number of samples with smoke and fire	0	0

During the voltage surge test, a high-speed camcorder was used to record the arcing events. Since the frame rate was 600 fps and only two frames captured arcing in an arcing event, the duration of the arc was estimated to be approximately 1.7ms, or one-tenth of the 60Hz 120VAC voltage cycle. Figure 47 shows the two frames arc captured in an arc event.

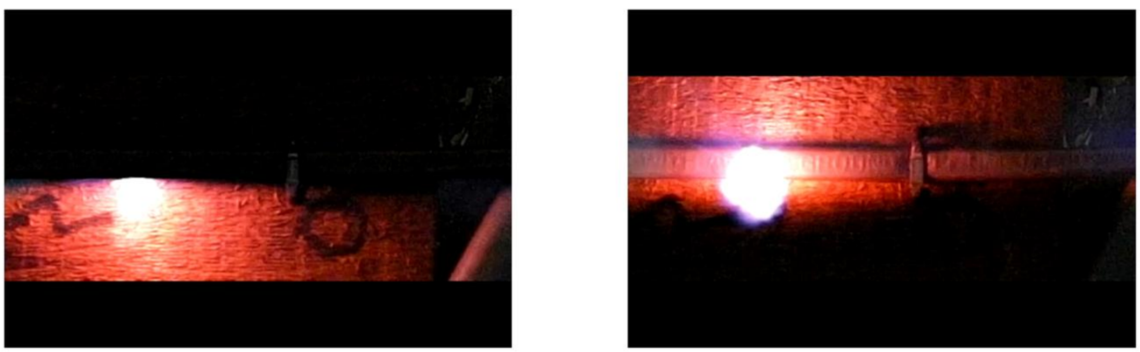


Figure 47 – Voltage surge generated electrical arc. On the left is the 1st image with arc, on the right is the 2nd image with arc.

In the tests, the maximum voltage and current applied to the NM cable sample through the circuit breaker are 120VAC and 100A to provide a maximum arcing power of 12kW. With an arc duration of 1.7ms, the maximum energy released in this arcing event was less than 200 Joules. Previous research has estimated that the minimum energy to ignite the NM cable insulation is 2000 Joules[28]. Since a single arcing event is unlikely to ignite the NM cable, data were developed on arcing and subsequent ignition of the NM cable insulation from one hundred 6kV surges using the UL 1499 transient waveform.

For these tests, the NM cable samples were damaged with 7ft-lb force hammer blows using the hammer impact simulator. Table 22 shows the test results.

Table 22 Repeated Voltage Surge Test

Sample	Peak breakdown voltage			Arcing	Ignition
	Before surge test	After 100 surges	After 300 surges		
1	4.2kV	3.6kV	1.6kV	Yes	No
2	1.6kV	3.8kV	0.9kV	Yes	No
3	4.8kV	1.8kV	shorted after 208 surges	Yes	No
4	3.3kV	1.8kV	0.7kV	Yes	No
5	5.6kV	4.5kV	1.7kV	Yes	No

The test results in Table 22 indicate that one hundred 6kV voltage surges to the same damaged area may not be able to ignite the NM cable.

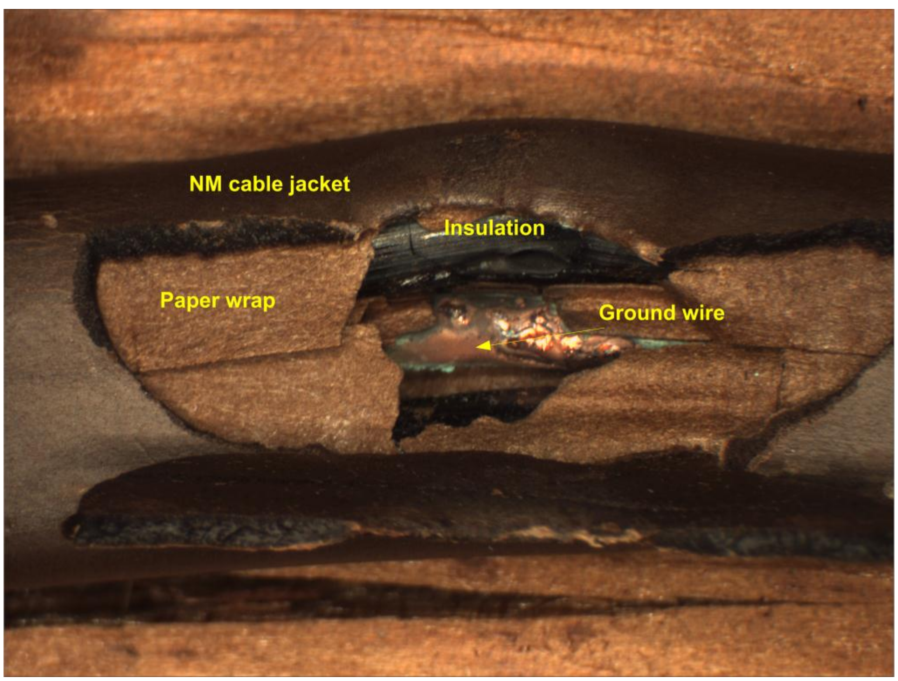


Figure 48 - Arcing area of damaged NM cable

Figure 48 is an image of arcing area of a damaged, then aged NM cable sample, simulating the effects of cable aging after it was damaged during installation. The image shows that there is an area of electric arc erosion on the ground wire and there is a crack on the conductor insulation. However, ignition was not observed for these tests.

Summary of Combination Effect of Damage and Thermal Degradation

- Over-driven staples may not initially reduce the conductor insulation breakdown voltage significantly, but the test result in Table 20 indicates that it leads to faster aging degradation for Cable B.
- No electrical arcing was observed from the over-compressed areas on the NM cable samples during the voltage surge testing.
- Electrical arcing was observed on 9 out of100 hammer-damaged NM cable samples.
- Electrical arcing was observed on 2 out of100 hammer-damaged and thermally aged NM cable samples.
- The test data indicate that the duration of the electrical arcing in the hammer-damaged area was about 1.7ms and the single electric arc event observed did not ignite the NM cable insulation materials.
- No sustained arcing and insulation ignition were observed during the repeated voltage surge test of 300 6kV voltage surges in parallel with 120VAC applied to the NM cable sample under the test.
- The test data indicate that the arcing event may further reduce the breakdown voltage (Table 22). One of the five samples in the test was shorted after 208 arcing events induced by the voltage surges. This short circuit blew a 20A fuse in the 120VAC test system, but it did not trigger the 20A circuit breaker in the system.

Summary of Key Findings

1. Commercially available NM cables in the USA have plasticized PVC-based cable insulation materials and may differ in the type of plasticizer used. The dielectric breakdown of new NM cables sampled had electrical breakdown voltage in excess of 15kV.
2. Common NM cable installation tools such as hammers or staple drivers can result in damage to the cable insulation.
    a. A misaligned staple may puncture the conductor insulation. Once punctured, the insulation breakdown voltage is down to the level of an air gap comparable with the insulation thickness, which is around 1.5kV.
    b. Overdriving a staple does not significantly reduce the NM cable breakdown voltage initially.
    c. A hammer blow of 7 ft-lb is 90% to 100% likely to reduce the insulation breakdown voltage below 6 kV, depending on the type of the cable. A hammer blow of 5 ft-lb is 37% to 100% likely to reduce the insulation breakdown voltage below 6 kV, depending on the type of the cable.
3. It was found that NM cables may age during their service life resulting in reduced electrical breakdown voltage due to the loss of plasticizer. This aging process was accelerated using elevated temperatures and a relationship was found between breakdown voltage and weight loss (primarily from loss of plasticizer). The results showed that thermal aging of an over-compressed NM cable from installation can lead to faster reduction of the electric breakdown voltage. However, these results were only based on Cable B data.
4. Electrical arcing was observed in the hammer-damaged area of NM cable samples under the voltage surge test (UL1449). The duration of these electrical arcs were about 1.7ms, and test result showed that the single arc event did not ignite the NM cable insulation materials. The number of arcing events compared to surge events was small (9 out of 100 for hammer-damaged cables).
5. Since the energy associated with the 1.7ms arc in the voltage surge test is only about 200 Joules, a single voltage surge event is unlikely to ignite the NM cable insulation material at room temperature. However, this damage will remain and therefore could increase the likeliness of forming a new and stronger carbonized path according to the test results shown in Table 22 (*i.e.*, more conducive to sustain arcing).
6. The repeated voltage surge tests however showed that a hammer-damaged NM cable could not be ignited with three hundred 6kV voltage surges using UL1499.

Discussion and Conclusions

This work shows that NM cable damage and/or aging can reduce the breakdown voltage of the cable insulation. Of the damage mechanisms tested, it is observed that hammer impact can inflict the most significant immediate damage to NM cable insulation. The thermal aging data indicate that as cable is aged its breakdown voltage will tend to fall, eventually falling below 6 kV. The concern is that lowered breakdown voltages increase the probability of formation of carbonized paths and arcing, since lower-voltage surges occur more frequently. This suggests that a combination of impact damage to NM cable during installation, followed by aging of the cable, may lead to a fire hazard over long periods of time. However, the results from this investigation did not demonstrate the formation of sustained electrical arcing.

In addition of a need to break down the cable insulation and formation of a carbonized path to initiate arcing, ignition of the cable insulation and/or surrounding material typically requires sustained arcing with sufficient energy release. To understand whether voltage surges can induce sustained electrical arcing, 100 damaged and aged NM cable samples were tested per the UL1449 (Standard for Surge Protective Devices). The test result showed that despite breakdown of the dielectric, there was no sustained arcing or ignition of the insulation. This is because the voltage surge is of a very short duration (50 μs) followed by 120VAC arcing that stopped before the zero crossing (1.7 ms). The zero crossing in an AC supply tends to extinguish the arcing event, with a re-strike requiring the continued presence of a well-defined carbonized path. The short arcing events found in the UL1449 tests show that the carbonized paths formed tend to be small and are destroyed during the arcing event (since no re-strike of the arc was observed).

In order to evaluate whether subsequent voltage breakdown occurrences further lower dielectric performance, 300 voltage surges (in parallel with 120VAC supply. Figure 46) were applied to each of five selected hammer-damaged NM cable samples and the breakdown voltages were measured before and after the voltage surges. The test result shows that the hammer-damaged NM cable samples did not ignite after 300 arcing events.

Since the plasticized PVC compounds exhibit time-dependent, viscoelastic behavior, the response of the NM cable structure (external jacket and insulation) to external damage may not manifest itself for months or years after the time of initial damage. This effect was reflected in the aging experiments with NM cables secured with over-driven staples, where the breakdown voltages continued to degrade with time. Though characterized through these aging studies, the time-dependent effects of plasticized PVC compounds could be evaluated by Dynamic Mechanical Analysis (DMA) under various conditions of temperature and frequency (isochron or Master Curve analysis). The effects of different plasticizer loadings, type and even filler level may affect the relaxation process and ultimately breakdown behavior. This would add a more fundamental understanding to the physical mechanisms involved when NM cable is subjected to sustained compressive stresses, such as through stapling or being compressed within a wall.

The data included in this work demonstrates a relationship between breakdown voltage and insulation weight loss. Leveraging these data from the accelerated aging tests, may allow for the development of a mathematical model that characterizes insulation aging with electrical performance in the field. This model would support an ability to predict aged cable performance under a variety of conditions, including damaged cable and undamaged cable in elevated-temperature environments.

In summary, the work described here shows that damage and degradation of a residential NM cable can lead to an arcing event, through voltage surges that break down the cable insulation and ignite arcing.

However, the test results also indicate that the breakdown event is unlikely to initiate arcing that is sustained long enough to ignite the cable insulation or surrounding materials. In this study, arcing for hammer-damaged cable exhibited arcing during less than 10% of the surge events, and exhibited arcing that lasted over a single half-cycle. The arcing observed in this study is much shorter than what is required for an AFCI to react to the event (eight arcing half-cycles within 0.5 seconds, per UL1699); however, the energy released in that short event is not expected to ignite the cable insulation.

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