INVESTIGATION AND ANALYSIS OF THERMAL AGING OF XLPE AND PVC CABLE INSULATION MATERIALS MANUFACTURED IN SAUDI ARABIA

By

Ali Muhammad Ali Abu-Gurain

A Thesis Presented to the

DENSHIP OF GRADUATE STUDIES

In Partial Fulfillment of the Requirements

For the degree

MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

KING FAHD UNIVERSITY

OF PETROLEUM & MINERALS

Dhahran, Saudi Arabia

JUNE 2003

KING FAHD UNIVERAITY OF PETROLEUM AND MINERALS

DHAHRAN 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by Ali Muhammad Ali Abu-Gurain under the direction of his thesis advisor and thesis co-advisor, and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE IN ELECTRICAL ENGINEERING.

Thesis Committee

Dr. M. H. SHWEHDI (Thesis Advisor)

Dr. M. A. MORSY (Thesis Co-advisor)

Dr. J. M. BAKHSHWAIN (Member)

Dr. S. M. SULTAN (Member)

Dr. K. R. SHELTAMI (Member)

Dr. J. M. BAKHSHWAIN
Department Chairman

Prof. OSAMA A. JANNADI
Dean of Graduate Studies

Date

Dedicated to my parents, my wife, my daughter Zahra, and my sons Mohammed and Haider.

ACKNOWLEDGEMENT

All dues be to Almighty Allah without his guidance, protection and sustain I was not able to finish my studies and all my life deeds are for Allah.

Acknowledgement is due to the King Fahd University of Petroleum & Minerals for supporting this research.

I wish to express my appreciation to Dr. M. Shwehdi for giving attention to me in order to complete my graduate study. Also, I'm appreciating his highly assistance in selecting the research subject, and his efforts in supervising me during the research period.

I would like to thank Dr. M. Morsy who supervise my experimental work and trained me on using the ESR spectrometer. Also, I express my gratitude to him for his unfailing help, criticism, and encouragement in the completion of this work.

I also wish to thank my thesis committee members, Dr. J. Bakhshwain, Dr. K. Sheltami and Dr. S. Sultan, for their valuable discussions.

At the end I would like to thank Mr. Yousuf Al-Yousuf for his encouragement and reporting Dr. M. Shwehdi concerns to my father.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

THESIS ABSTRACT

Name:	**Ali Muhammad Ali Abu-Gurain**
Title:	**Investigation and Analysis of Thermal Aging of XLPE and PVC Cable Insulation Materials Manufactured in Saudi Arabia.**
Major field:	**Electrical Engineering**
Date of degree:	**June 2003**

Electrical power distribution systems utilize thousands of kilometers of cable materials of different voltage levels. Power cables generally consist of a metal conductor surrounded by an insulation layer. Petrochemical industries in Saudi Arabia and others provide raw materials for cable industries. Polyvinyl chloride (PVC) has usually been the polymer of choice in power cable construction due to its easy processing and good insulation performance. Even now, with the trends toward using Cross-linked polyethylene (XLPE) and other polymers, PVC still makes up approximately 50 % of the polymer volume used in cable construction.

The whole year around severe weather environment of the Kingdom adds tremendous factors in stressing cable materials and shortens their lifetime. The Kingdom petrochemical industries are striving to improve the quality of the plastic raw materials. On the other hand, cable industry has also made noticeable progress in the production of higher voltage level cables. As far as high voltage cables are concerned, electrical field strength and temperature are, in general, the prevailing stresses producing insulation aging. These effects cause partial discharges in the insulation material that will lead definitely to a short circuit. Unexpected cable faults may cost utilities, as well as customers, large financial losses.

The proposed study will provide and conduct direct testing and investigation of thermal aging on widely used cable insulation materials (PVC and XLPE) to determine their endurance characteristics, Raw and manufactured insulation materials will be brought from major Saudi cable factories. Mainly, weight loss and electron spin resonance (ESR) spectral studies and analysis will be carried out to characterize and simulate the thermal stress to evaluate the quality and life-time of the insulation materials. The results of PVC and XLPE can be extended from life tests to the application of these materials for higher quality and to the improvement of cable materials.

ملخص الرسالة

الاسم : **علي محمد علي أبو قرين**

عنوان الرسالة : **بحث و تحليل التهالك الحراري لعوازل الأسلاك الكهربائية من نوع البولي إيثيلين المتفرع (XLPE) و البولي فينيل كلوريد (PVC) المصنعة في المملكة العربية السعودية.**

التخصص : **هندسة كهربائية**

تاريخ التخرج : **يونيو ٢٠٠٣ م – ربيع الآخر ١٤٢٤ هـ**

تستهلك أنظمة توزيع الطاقة الكهربائية آلاف الكيلومترات من الأسلاك الكهربائية ذات مستويات مختلفة من الجهد. تتألف كابلات القوى الكهربائية من موصل مغلف بمواد عازلة. يتم توفير المادة الخام للعوازل المستخدمة في مصانع الكبلات الكهربائية عن طريق الصناعات البتروكيميائية بالمملكة العربية السعودية و دول أخرى. تستخدم مادة البولي فينيل كلورايد في صناعة الأسلاك الكهربائية بشكل عام و ذلك نظراً لسهولة معالجتها و أدائها الجيد كمادة عازلة. و مع ازدياد التوجهات لاستخدام مادة البولي إيثلين المتفرع و مواد بوليمرية أخرى إلا أن مادة البولي فينيل كلوريد ما زالت تشكل ما يقرب من ٥٠% من كمية البوليمر المستخدم في صناعة الأسلاك الكهربائية.

تعمل الصناعات البتروكيميائية في المملكة على تطوير جودة مواد البلاستيك الخام، و لقد قامت مصانع الأسلاك الكهربائية بتقدم ملحوظ في إنتاج كابلات ذات جهد عالي. إن لقسوة الظروف المناخية في المملكة تأثيراً كبيراً على المواد المستخدمة في صناعة الكبلات الكهربائية مما يقلل من عمرها الافتراضي. كما أن قوة المجال الكهربائي و شدة الحرارة غالباً ما تكون من العوامل المؤثرة على تهالك المادة العازلة في الكابلات ذات الجهد العالي. هذه التأثيرات تسبب في حدوث تفريغات جزئية في المادة العازلة و بالتالي تؤدي إلى قصر الدائرة. و التي تؤدي إلى أعطال الأسلاك الكهربائية غير المتوقعة و إلى خسائر مالية للمؤسسات و الأفراد.

في هذا البحث تم إجراء اختبارات مباشرة و دراسة عن التهالك الحراري على أكثر المواد العازلة استخداماً و هي البولي فينيل كلوريد (PVC) و البولي إيثلين المتفرع (XLPE)، و ذلك بغرض تحديد خصائص التحمل للمواد الخام و كذلك المواد المعالجة المصنعة بالمملكة. ولقد تم دراسة و تحليل نتائج اختبارات فقدان الوزن و طيف الرنين الإلكتروني بغرض توصيف و محاكاة الإجهاد الحراري و كذلك الحرارة المتولدة بسبب تيار الحمل الكهربائي و ذلك لتقييم الجودة و فترة العمر للمواد العازلة. هذه النتائج ستساعد مصانع الأسلاك الكهربائية لتطوير و تحسين جودة المواد العازلة لتكون ذات خصائص أفضل و قدرة تحمل أعلى للحرارة، و الذي بدوره يساهم في خفض التكاليف الناتجة من أعطال الأسلاك بشبكات القوى الكهربائية.

CHAPTER # 1

INTRODUCTION

Power underground cables generally consist of a metal conductor surrounded by multiple insulation layers; this insulation is for protection against mechanical damage and water contact, jacketing is extruded around one or more of the insulated conductor wires. Medium and higher voltage power cables have additional semi-conductive layers between conductor and insulation and between insulation and jacketing.

In power cables industries the easy processing and good insulation performance of polyvinyl chloride (PVC) make it the polymer of choice in power cable construction. The main disadvantages of PVC include relatively high dielectric constant and dissipation factor. Although the low thermal stability of PVC has been an area of intensive research, the relationship between microstructure and degradation behavior is still not fully understood. However, the recent technological improvement in insulating materials manufacturing trends have directed cable industry toward using cross-linked polyethylene (XLPE) and other polymers that are more resistant to degradation from treeing, in addition to PVC, in EHV cable construction [1, 2]. Much of these insulating materials are colored to standard shades for ready identification. The colorants must be carefully chosen to maintain the insulation properties of the polymer.

During insulation manufacturing, plastics are exposed to heat that lead to degradation. The final product depends on the type of plastic, the additives used, and the processing temperature. Although degradation can not be eliminated completely, it must be held to a minimum to keep the quality of the final products high. This degradation may cause a homolysis fission of many of the bonds in the used polymers to take place that will introduce stable organic free radicals [3]. Organic free radicals are generally short lived. Their lifetime can be increased in the presence of suitable stabilizing matrix due some expected structural changes such as cyclization and formation of polyatomic rings [4].

Aging process in polymers is initiated and accelerated by many factors such as electric field, temperature, moisture, ionizing radiation and light. These factors can play an essential role in cable aging, either independently or simultaneously according to cable operating conditions and environment.

The aging process leads to structural changes in the polymer. Oxidation and subsequent disintegration of macromolecules is the most important internal degradation process irrespective of the aging factors being applied [5]. It has been postulated that electrical breakdown is due to polymer oxidation or oxidation together with mechanical stresses.

The ac-breakdown voltage of a polyethylene (PE) cable is affected by heating due to overloads [6]. Even slight overheating may have a harmful effect through density changes of the PE near the inner conductor. Partial melting and recrystallization that occurs due to heating and cooling can change the density.

The standard procedure for thermal endurance characterization of electrical insulating materials is to perform aging tests at three or more constant temperatures on suitably selected samples according to IEC Standard 216 [7]. In order to reveal the degree of aging, the aged specimens are subjected to diagnostic procedures using chemical-physical, electrical, and mechanical properties. The thermal endurance lines of the tested materials are obtained by selecting end point criteria.

It is well known that electron spin resonance (ESR) spectroscopy is the only technique established to detect radicals [8, 9]. It has been used to detect and characterize free radicals from different sources [10]. Technological advancement made it feasible the comparative study between free radicals from the synthetic analogues such as rubber and plastic material. [11, 12]

The following discussion clearly points to the need of meaningful "accelerated" life tests which have the approval of the material suppliers, the cable manufacturers, and the ultimate users, i.e. the utility companies. Accelerated life tests have been performed for many years and yet their validity is still questioned. This uncertainty is believed to be a reflection of the ignorance regarding the significance of the interaction of the various stresses.

The urgency to develop meaningful accelerated life tests for underground solid dielectric cables is dramatically reflected in a multi-million dollar contract the U.S. Department of Energy has let to study the aging process in solid dielectric cables in 1977 and to develop aging tests for prediction of cable life [13]. There is a considerable apprehension that acceleration of one aging factor in combination with another may yield results that cannot be reliably extrapolated. There exists more apprehension about the validity of extrapolation when two factors are accelerated simultaneously.

1.1 STATEMENT OF PROBLEM

Insulations of electric power cables are stressed by rapid expansions and development that leads to cable overloading plus the sever weather environment of the kingdom of Saudi Arabia, that adds tremendous factors in stressing cable insulations and shortens their lifetime. The petrochemical industries in Saudi Arabia are striving to improve the quality of the polymers raw materials used in cable insulation industries, yet there are no research and development (RD) laboratories to make such improvements.

It is known that in high voltage cables, electrical field strength and temperature are the most stresses producing insulation aging. This aging process will lead definitely to failure, which may cost utilities as well as customers large financial losses.

The proposed research provides and conduct direct testing and investigation of thermal aging on widely used cable insulation materials (PVC and XLPE) to determine their temperature endurance characteristics. Raw and manufactured insulation materials will be brought from major Saudi cable factories. Mainly, weight loss and electron spin resonance (ESR) spectral studies and analysis is carried out to characterize and simulate the thermal stress to evaluate the quality and life-time of the insulation materials. The results of PVC and XLPE can be extended from life tests to the application of these materials for higher quality and improvement of cable materials.

1.2 INVESTIGATION METHODOLOGY

The investigation is carried out in four phases:

Phase I: during the initial phase, raw samples used in cable insulation manufacturing of pure and manufactured PVC and XLPE from locally available industries are obtained.

Phase II: Jeddah Cable Company provided all the needed samples. Weight loss and ESR experiments at room temperature are performed on the material as received and without any further treatment and before thermal degradation takes place.

Phase III: a designed experimental approach is used to determine the temperature dependent of the insulation materials using ESR spectrometer. The results yield vast information about stability of plastics and relative quantity of free radicals formed at different temperatures.

Phase IV: the obtained results are plotted and tabulated for further analysis, interpretation and correlation to reveal the properties of such materials and their thermal endurance.

1.3 THESIS ORGANIZATION

The thesis consists of seven chapters. The first chapter serves as the introduction of this research. The cables and insulation review and background are introduced in chapter 2 in which essentials of electrical cable are summarized.

In chapter 3 the breakdown characteristics and dielectric aging of cable insulations are demonstrated. Aging and failures, effects of thermal aging, and most of the references on insulating materials, mainly PVC and XLPE are presented in chapter 4. Chapter 5 will be confined to the practical procedures and work methodology, results of the experiments and tests, data analysis, manipulation and discussions including weight difference and ESR spectrum. Followed by chapter 6, which include the conclusion and recommendations of the research. References are provided in chapter 7.

CHAPTER # 2

CABLES BACKGROUND:

CABLES AND INSULATIONS REVIEW

2.1 POWER CABLES

Power cable includes the following types of cable:

- High voltage primary distribution cable
- Secondary distribution cable (underground and overhead lines)
- Commercial and industrial low and medium voltage power cable
- Control cable

Most insulated overhead wirings are in secondary distribution lines carrying 300-600 volts. PVC is almost never used for insulation of power cables above 600 volts, due to its lower insulating property [14]. PE types employed for power cable are low-density cross-linkable (XLPE), thermoplastic medium-density polyethylene (MDPE) and high-density polyethylene (HDPE) grades. In the past, MDPE has been the insulating polymer of choice for overhead cables, but XLPE has taken much of this market. The peroxide-cure XLPE cable insulation is slightly more durable and offers better flame retardant compounding ability as compared to moisture-cure XLPEs [14].

PVC and XLPE are both used for power cable jacketing in Canada. Underground wiring, buried with or without ducting, is insulated with XLPE, MDPE or HDPE and can have a PVC jacket, a XLPE jacket, or none at all. The removal of jacketing allows larger diameter conductors, carrying a higher capacity, to be used in ducts.

Low and medium voltage power cable is used to distribute power in large buildings, industrial sites, and transit systems. Medium voltage control cable is used to regulate voltage on large electrical equipment. There is a large amount of PVC jacketing used for these two applications, due to fire code restrictions on flame propagation. To date, there has been very little flame-resistant PE or XLPE jacketing used in these higher risk applications. However, in certain areas such as in certain commercial and transit cable installations, there has been increasing use of low-smoke, halogen-free jackets because of the other fire risks of smoke emission, corrosivity and toxicity. Many transit systems have specified low-smoke, halogen-free cables for underground areas.

In the United States, a PVC and nylon construction is used for insulating wire with voltages less than 1 kV. In Europe, PVC is employed in insulation for cables up to 5000 volts, but heat losses become unacceptable beyond that. PVC is more susceptible to moisture permeation, but is preferred for power cable jacketing because of its superior flame-resistance, flexibility, good weather ability and low cost.

An insulated power cable seems to be a relatively simple electrical device. However, this cable is an electrically sophisticated system of components. To understand it, a brief introduction of its components and basics of operation is outlined next. For simplicity, the cable components description shall be restricted to a single-conductor cable, and these fundamentals also apply to multiple-conductor cables.

2.2 CONSTRUCTION OF CABLES

2.2.1 NON-SHIELDED CABLE

There are two basic elements in a non-shielded cable, namely conductor and the electrical insulation, or the dielectric. In some cable designs, an outer jacket is used as shown in Figure 2.1 [15].

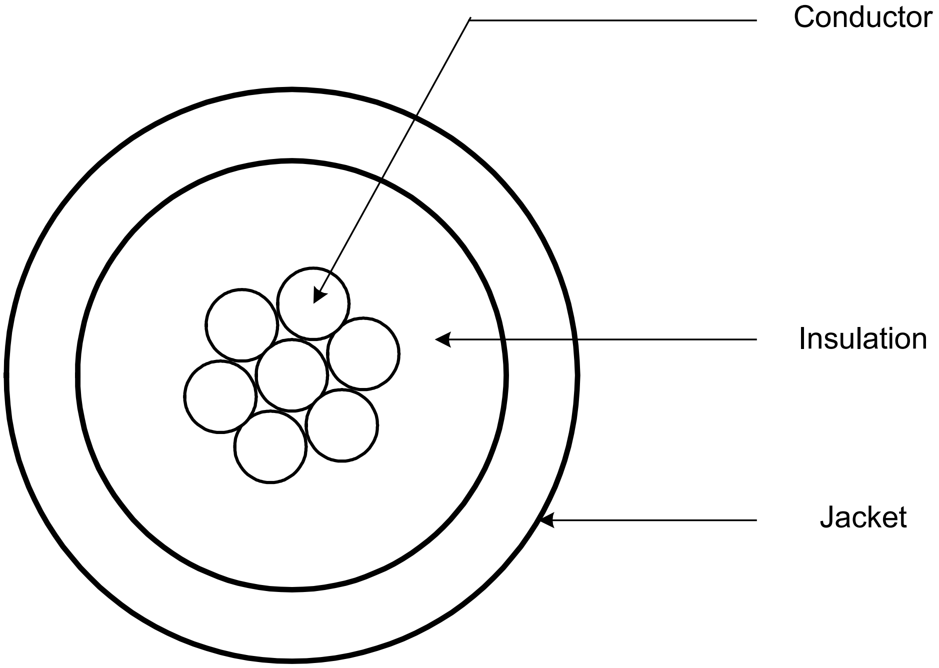


Figure 2.1: Construction of a non-shielded cable.

2.2.1.1 CONDUCTOR

The conductor can be aluminum or copper but generally copper conductors are preferred with either a solid or stranded cross section. The main reason to use copper in cables over aluminum is due to its high conductivity, this enables power loss (heat generated) as minimum as it could be. The reason for stranded conductors is improved flexibility, and they can also be compressed, compacted, or segmented to get the desired flexibility, diameter, and load current density.

2.2.1.2 ELECTRICAL INSULATION OR DIELECTRIC

The second component of a non-shielded cable is the electrical insulation. Electrical insulation must provide adequate physical and electrical properties between the energized conductor and the nearest electrical ground to prevent electrical breakdown. The insulation thickness required to provide the necessary physical protection against damage for low-voltage cables, 600 volts and below, is more adequate to provide the necessary dielectric strength. [15]

2.2.1.3 JACKET

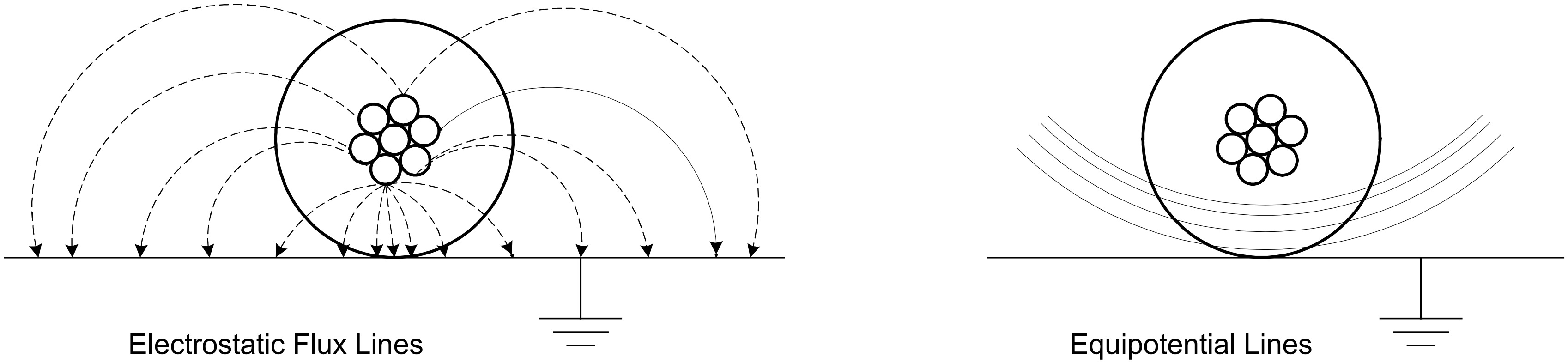
It is a material that provides a protection in mechanical and chemical properties applied as a direct covering over cable insulation. The choice of materials for cable design to satisfy any given combination of installation and environmental conditions can be more critical than the electrical requirements. There are several materials such as PVC and nylon, are used as jackets to provide the necessary chemical, physical, or thermal protection required by the application.

2.2.1.4 DIELECTRIC FIELD

The dielectric field is another consideration in the design and application of cables. There is a dielectric field present when the conductor is energized in all electrical cables, irrespective of their voltage ratings. Electrostatic flux lines and equi-potential lines between the conductor and electrical ground represent this dielectric field [15].

There are electrostatic lines of flux created within the dielectric when a conductor is energized. The density of these flux lines depends on the magnitude of the potential difference between the conductor and electrical ground.

The distance between the equi-potential lines represents the voltage differential in the insulation. For a given voltage differential, these lines are closer together nearer the conductor. Figure 2.2 shows the electrical field of a non-shielded cable in contact with a ground plane [15]. It does not take into account



Electrostatic Flux Lines

Equipotential Lines

Figure 2.2: Dielectric field of low-voltage non-shielded cable in contact with electrical ground.

the difference in the dielectric constants of the cable insulation and the surrounding air.

2.2.2 SHIELDED CABLE

The basic components of a shielded cable are shown in Figure 2.3 [15]. The fundamental difference between non-shielded and shielded cable is the inclusion of conducting components in the cable system.

2.2.2.1 CONDUCTOR

The conductors used in shielded cables are equivalent to those used in non-shielded cables.

2.2.2.2 CONDUCTOR SHIELD OR SCREEN

The conductor shield is usually a semi-conducting material used to shield out the conductor contours, and applied over the conductor circumference. Due to the presence of this shield, the shape of the outer conductor contours will not distort the resulting dielectric field lines. This layer also provides a smooth and compatible surface for the application of the insulation.

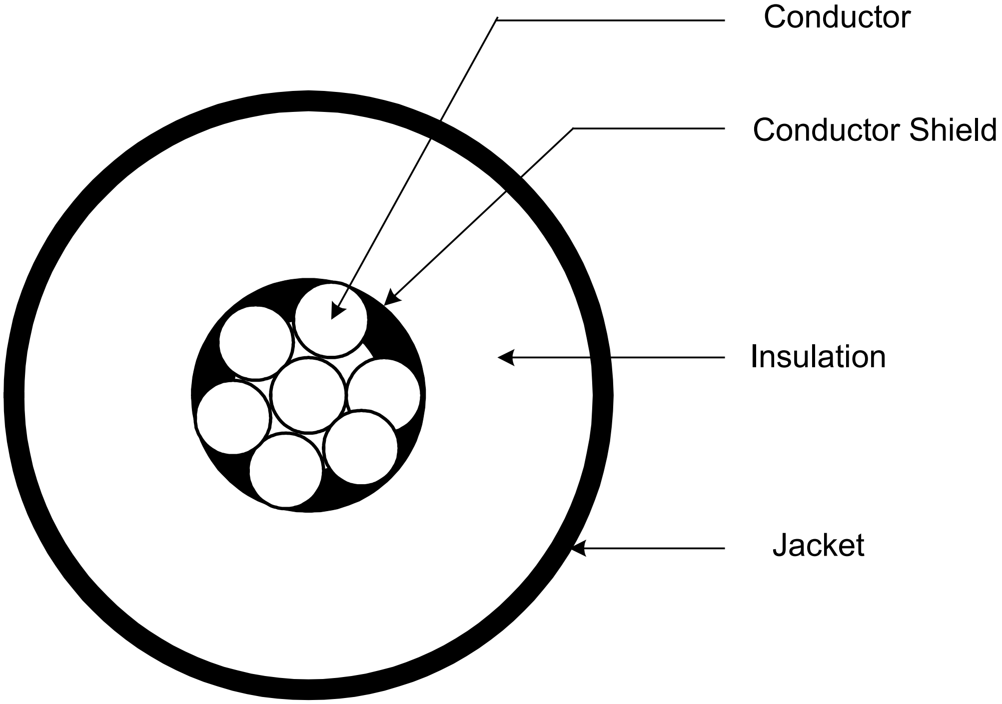


Figure 2.3: Construction of shielded cable.

2.2.2.3 ELECTRICAL INSULATION OR DIELECTRIC

The third component of a shielded cable is the electrical insulation. The operating voltage influences the insulation thickness required to provide the necessary dielectric strength. The insulating material of shielded cable is different from non-shielded cables due to the operating voltage.

2.2.2.4 INSULATION SHIELD OR SCREEN

It is a two-part system composed of an auxiliary and a primary shield. An auxiliary shield is usually a semi-conducting nonmetallic material applied over the dielectric circumference. It must be smooth, compatible with the insulation. A primary shield is a metallic shield, wire or tape, over the auxiliary shield. It must be capable of conducting the summation of leakage currents to the nearest ground.

The primary shield by itself cannot achieve acceptable physical contact with the dielectric surface. A resilient auxiliary shield is necessary to eliminate arcing between the dielectric surface and the primary shield.

2.2.2.5 DIELECTRIC FIELD

Electrostatic flux lines are spaced symmetrically and perpendicular to equi-potential lines. The presence of the shielding results in field lines as shown in Figure 2.4. [15]

In a shielded cable all the voltage difference between conductor and electrical ground is maintained within the cable. For a non-shielded cable the voltage difference between conductor and ground is divided between the cable dielectric and any intervening air or other materials.

2.3 INSULATING MATERIALS USED IN CABLE INDUSTRY

Insulation is a material having good dielectric properties used on wire components in cable usually as direct covering on conductors. It is an important component of the wire. Insulation selection is determined by a number of factors such as stability and long life, dielectric properties, resistance to high temperature, resistance to moisture, mechanical strength and flexibility. It is necessary to select a cable with the type of insulation that fully meets the requirements of the application. There is no single insulation that is ideal in every one of these areas for example, compressor motors used in refrigerators must use wire insulations that are compatible with the refrigerants to which the wire is exposed. Also, gasoline pumps need wire that will not deteriorate in the presence of gasoline vapors. There are some applications where the wire must be resistance to liquids or chemicals. The best insulating material for an application

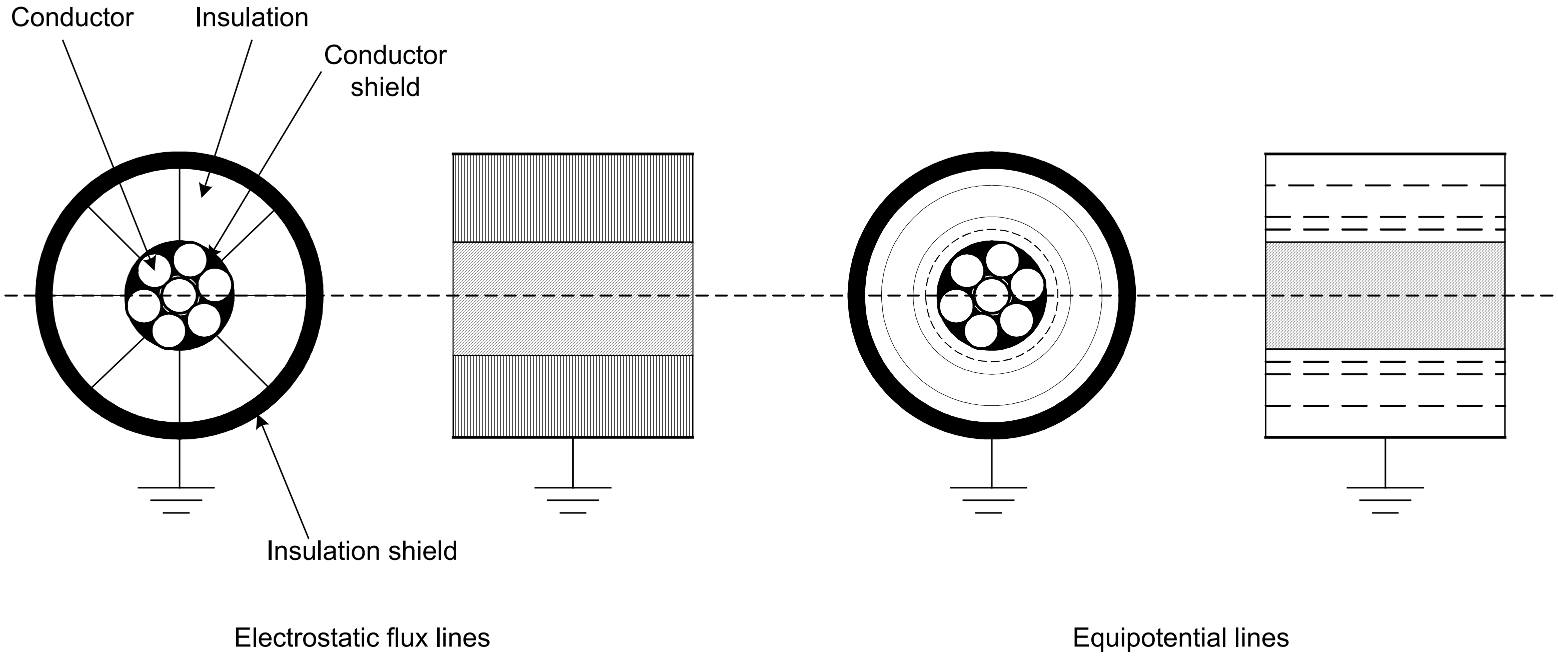


Figure 2.4: Dielectric field of shielded cable.

is selected based on the requirements. The selection may involve test of many different performance properties.

Thermoplastic and thermoset are two major subdivisions of the large family of insulation materials [15,16]. The division is based on their behavior toward heat [16]. Thermoplastic are materials that are softened by heat. The material will become rigid again upon cooling. This process of molding and firming these materials by heating and cooling can be repeated. Thermoset are materials, which are softened once heated during one stage of processing. They can be molded and extruded at this state after which they are cured. After completing the setting process, they cannot be softened again on subsequent heating. There are various types of insulating materials; some of them are mentioned in the following.

2.3.1 INSULATION TYPES

2.3.1.1 POLYVINYL CHLORIDE (PVC)

PVC compounds can be formulated to provide a broad range of properties from the standpoint of electrical, physical and chemical characteristics. PVC has high dielectric strength and good insulation resistance. It is inherently tough and resistant to flame, moisture, and abrasion. Resistance to ozone, acids, alkalies, alcohols, and most solvents is also adequate. Compounding can impart resistance to oils and gasoline. PVC exhibits little or no water absorption. Since it is chlorinated, PVC also possesses natural flame retardant qualities. Based on the specific formulation, temperature ratings range from 60° to 105° C.

2.3.1.2 POLYETHYLENE (PE)

Polyethylene (PE) is a good insulation in terms of electrical properties. It has a low and a stable dielectric constant over all frequencies, a very high insulation resistance and resistance to chemicals and moisture [15,17]. In terms to flexibility, polyethylene can be stiff to very hard, depending on molecular weight and density. As the density increases, the hardness, yield strength, stiffness, heat and chemical resistance also increase [15]. Carbon black or a suitable inhibitor is added to screen out ultra-violet (UV) radiation, because UV radiation can degrade both physical and electrical properties [15].

2.3.1.3 CHLOROSULFONATED POLYETHYLENE (CSPE)

It is a thermoset material and known as Hypalon. CSPE is made by adding chloride and sulfonyl groups to polyethylene. This process changes the stiff plastic into a rubbery polymer, which can be cross-linked in many ways. CSPE has excellent mechanical properties such as tear tensile strength and abrasion resistance. In addition, it has good weather, ozone, oil, and chemical resistance. The material also has low moisture absorption, excellent resistance to flame and heat, and good dielectric properties. [15,17]

2.3.1.4 POLYPROPYLENE (PP)

Polypropylene (PP) is similar in electrical properties to polyethylene [17]. This material is primarily used as insulation, and it is harder than polyethylene that makes it suitable for thin wall insulations. It has excellent insulating properties and is extremely light weight [18].

2.3.1.5 POLVINYLIDENE FLUORIDES (PVDF), KYNAR

Has great mechanical strength, superior resistance to abrasion and cut-through and substantially reduced cold-flow which makes it an excellent back plane wire insulation [17,18]. Kynar is self-extinguishing and radiation resistant.

2.3.1.6 FLUROINATED ETHYLENE PROPYLENE (FEP)

It is extrudable in a manner similar to PVC and polyethylene. It has low dielectric constant and is flame and ignition resistant. Also, it is chemically inertness and has a service temperature of 200°C. [17,18]

2.3.1.7 TFE TEFLON

TFE Teflon is extrudable in a hydraulic ram type process. Lengths are limited due to the amount of material in the ram, thickness of the insulation, and preform size. TFE must be extruded over silver or nickel coated wire. The nickel and silver coated designs are rated at 260°C and 200°C respectively. [17]

2.3.1.8 SILICONE

It is a very soft insulation that has a typical temperature range from -80°C to 250°C. It has excellent electrical properties, ozone resistance, low moisture absorption, weather resistance and radiation resistance. It has low mechanical strength and poor scuff resistance. Silicone rubber burns slowly and forms a non-conductive ash. This in turn can maintain the integrity of the electrical circuit. [17]

2.3.1.9 ETHYLENE PROPYLENE RUBBER (EPR)

EPR is a thermoset material synthesized from ethylene, propylene and a third monomer [15]. It is cross-linked, and a high temperature rubber insulation. It has excellent electrical properties combined with outstanding thermal stability and flexibility. It's resistance to compression, cutting, impact, tearing and abrasion is good. Acids, alkalis and many organic solvents do not attack EPR. It is also highly moisture resistant. It has temperature ratings up to 150°C. [17]

2.3.1.10 CROSS-LINKED POLYETHYLENE (XLPE)

It is rated up to 150°C [17]. Cross-linking changes thermoplastic polyethylene to a thermosetting material which has greater resistance to environmental stress such as cracking, cut-through, ozone, solvents and soldering than either low or high density polyethylene or non-cross-linked polyethylene. It can be cross-linked either chemically or irradiated. [17,18]

2.3.1.11 STYRENE BUTADIENE RUBBER (SBR)

SBR is flexible and has a good heat and moisture resistance. It must be jacketed for mechanical and chemical protection. Suitable for temperature ratings 75°C maximum [17].

Table I shows typical properties of some insulating materials [17].

2.3.2 JACKET TYPES

Jackets provide environmental protection over the insulation shielding

TABLE I: TYPICAL PROPERTIES of SOME INSULATING MATERIALS.

	PVC	**PE**	**XLPE**	**FEP**	**TFE**	**SBR**	**Silicone Rubber**
Specific Gravity	1.37	0.92	1.20-1.40	2.20	2.15	1.40	1.24
Tensile Strength (PSI x 1000)	1.5-3.8	1.4-2.4	1.8-2.5	2.3-3.1	2.6-6.0	0.5-1.5	0.6-1.2
Elongation, %	200-375	350-550	250-400	200-330	200-500	200-400	125-400
Service Temp. Range, °C	-55 to +105	-20 to +75	-65 to +150	-70 to +200	-70 to +260	-40 to +75	-70 to +200
Dielectric Strength V/MIL -.040" WALL	800	1050	700	950	950	500	400
Dielectric Constant 60 Hz to 1MHz	5.0	2.26	3.0	2.15	2.1	4.0	3.1
Water Absorption, % in 24 Hrs	<0.75	<0.02	<0.01	<0.01	<0.01	<1.0	<1.0
Flame Resistance	Self-Extinguishing	Supports Flame	Slow Burning	Non-Flammable	Non-Flammable	Slow Burning	Slow Burning
Ozone Resistance	Excellent	Good	Good	Excellent	Excellent	Excellent	Excellent
Flexibility	Good	Good	Good-Fair	Good	Good	Excellent	Excellent
Abrasion Resistance	Good	Good	Excellent	Excellent	Excellent	Poor	Poor

system. Jacket is applied over primary insulation, shields, cable components or over the cable itself [17]. It includes many of the primary insulating materials, containing nylon, neoprene, hypalon, ethylene-propylene rubber, polyurethane, etc. They serve several purposes, such as, providing mechanical, thermal, chemical and environmental protection to the insulated conductors they enclose. They also protect the characteristics of the underlying insulation.

Commonly used jacketing materials are extrusions of PE, PVC, Nylon and CSP. PVC, Nylon and PE are applied using thermoplastic extrusion lines in which the material is heated to the melting point and form it over the core. The material is then cooled and wound onto a reel. Because CSP is a thermoset material, some heat is used to soften the material so that it can be formed around the core. It is then cross-linked to obtain its full properties. Some jackets types are follows.

2.3.2.1 PVC

It is a thermoplastic inherently flame and abrasion resistant material that is specially compounded for general-purpose applications at temperatures to 105°C.

2.3.2.2 CPE

CPE is chlorinated polyethylene and is available in both thermoplastic and thermosetting versions. It has excellent flame resistance, chemical resistance and cold temperature properties. Temperature range is -40°C to 105°C.

2.3.2.3 TPE

It is thermoplastic elastomer or TPR. Thermoplastic rubber has mechanical characteristics of thermoset rubbers yet is a thermoplastic. They have excellent ozone and chemical resistance, excellent electrical properties and low water absorption. Temperature range is -70°C to 125°C.

2.3.2.4 NEOPRENE

Neoprene is a polychloroprene and is a thermosetting compound. It is flexible, has good oil, ozone, heat and weather resistance, specified for outdoor applications due to its weather, sunlight and cold temperature properties. It will not support combustion and resists abrasion and cutting.

2.3.2.5 CSPE

It is chlorosulfonated polyethylene (Hypalon - a DuPont trade name) and is a thermosetting compound. It can be formulated for almost total resistance to ozone attack, which can destroy many kinds of nonmetallic materials. It also exhibits good resistance to oxidation by sunlight, weathering, chemicals and high temperatures. Besides radiation resistance, it has fair cold temperature properties compared to neoprene. The material has low moisture absorption and good dielectric properties.

2.3.2.6 POLYURETHANE

Has exceptional resistance to oil, radiation, fungus, oxidation and ozone. It is unusually tough, has higher tensile strength and elongation, more abrasion resistance and better low temperature flexibility than neoprene. Its major disadvantage is poor resistance to steam, high temperatures and acids. But it has outstanding "memory" properties, making it an ideal jacket material for retractile cords. Since it is an expensive material, it is only specified when other jacket materials will not satisfy the requirements of the application.

Table II shows typical properties of some jacketing materials [17].

2.3.3 THE ROLE OF INSULATION IN ELECTRICAL SYSTEMS

The insulating material normally must withstand electric stress; however, it must also endure other stresses. In electric motor the torque is the result of the force created by current in the conductor and surrounding magnetic field. In

TABLE II: TYPICAL PROPERTIES of SOME JACKET MATERIALS.

	PVC	**PE**	**Nylon**	**FEP**	**TFE**	**Neoprene**
Specific Gravity	1.37	0.92	1.09	2.20	2.15	1.52
Tensile Strength (PSI×1000)	1.5-3.8	1.4-2.4	8.8-11.9	2.3-3.1	2.0-6.0	2.5-4.0
Elongation, %	200-375	350-550	150-380	200-330	200-500	300-500
Service Temp. Range, °C	-55 to +105	-20 to +75	-55 to +105	-70 to +200	-70 to +260	-30 to +90
Ozone Resistance	Excellent	Good	Good	Excellent	Excellent	Excellent
Weatherability	Good-Fair	Excellent-Good	Fair-Poor	Excellent	Excellent	Good
Flame Resistance	Self-Extinguishing	Supports Flame	Self-Extinguishing	Non-Flammable	Non-Flammable	Self-Extinguishing
Abrasion Resistance	Fair-Good	Good	Excellent	Excellent	Excellent	Excellent
Flexibility	Good	Poor-Good	Good	Good-Fair	Good	Excellent
Acid Resistance	Fair-Good	Excellent	Excellent	Poor	Excellent	Good
Hydraulic Fluid Resistance	Fair	Good-Fair	Fair-Poor	Good-Fair	Excellent	Good
Organic Solvent Resistance	Good	Fair-Poor	Poor	Good-Fair	Excellent	Good
Resistance to Tearing	Good	Good	Good	Excellent	Good	Good

cables a short circuit can create enormous mechanical forces between conductors. These aspects indicate that insulation must have electrical as well as mechanical properties that will isolate the conductor over normal and abnormal conditions.

The material becomes weaker at elevated temperatures and a failure may occur in the case of a thermoplastic because of the melting of the material. This can be a very short time failure, because of the short time required for the temperature to rise to the melting point. On the other hand, long term at elevated temperature can cause internal chemical effects in the material. For instance, internal polymerization can occur during which materials develop higher molecular weights. This can lead to higher tensile strengths, and hence to lower elongation capabilities. The material may become brittle where simple vibration or impact may cause a mechanical fracture.

When one adds to the inherent properties of the material the effect of environment, the prediction of insulation behavior becomes more complicated. As a simple example, the presence of air around a heated insulation can lead to simple oxidative degradation; depending upon the material involved this can mean either embrittlement or softening of the material. An obvious extension of this type of degradation is the effect of other chemicals in the atmosphere around the insulation. Solvents or other active chemicals can react with the basic insulating material to the detriment of the latter.

One factor which did not become obvious before the appearance of many new insulations is that of compatibility. If, for example, a given magnet wire insulation is impregnated with or dipped into a varnish, it is entirely possible that at room or elevated temperatures a chemical reaction can occur between this insulation and the varnish to the detriment of either or both.

The manufacturing process itself may constitute a damaging or aging action. The electrical insulation must be very hearty in order to withstand the mechanical abuse that it gets while being installed in equipment. Thus, the mechanical stresses are often very severe compared to the subsequent abuse the insulation gets in service. Normal in-service mechanical stresses may originate from vibration caused by changing magnetic fields, as well as by most mechanical movements. A second stress that may seriously influence life expectancy is abrasion, which generally occurs due to sliding contact between insulation and metal as temperatures change from high to low values, or vice versa.

Historically, underground cables have been designed for 40 years performance. At that time, cable construction was based on oil impregnated cellulosic paper. Since then, demand for electricity has grown rapidly. Industry has found it more efficient to increase operating voltage rather than current, because the losses were so much greater in the copper than in the dielectric of the existing cables. However, at 550 kV, the dielectric loss is found to be almost as large as the conductor loss, which means that increases in voltage with existing systems do not result in increased efficiency [19].

At least 10 years ago, an attempt was begun to extend the use of low loss extruded dielectrics such as polyethylene, to voltages substantially above those e.g., 138 and 230 kV, for which they have been used commonly. This approach has received a setback during the past 5 years. A rash of failures in 5-10 years old 15 kV polyethylene insulated cables revealed the problem of trees. This phenomenon of partial breakdown, having the appearance of a small tree, was entirely unexpected and exemplifies the trouble one may run into when introducing a new system.

Much work is now being expended to explain the mechanism of treeing and to eliminate or reduce it. Use of hermetically sealed enclosures to exclude water and oxygen, as is done for paper-laminated structures, might eliminate the treeing problem, but at an increasing cost of the system.

With the development of new dielectric materials, additional temperature classes were added so that the temperature classification of materials agreed with that of equipment, as in Table III.

Three basic considerations were formally recognized which good designers and investigators had recognized all along:

TABLE III: TEMPERATURE CLASSIFICATION of DIELECTRIC MATERIALS.

Class	**Limiting hot spot temperature**
O	To 90 °C
A	105 °C
B	130 °C
F	155 °C
H	180 °C
C	Over 180 °C

1. All parts of electrical equipment do not necessarily operate at the same temperature. For example, if the hottest portion of equipment is at 150°C, there are other portions that may be under 100°C. Obviously, a material that will withstand the higher temperature is not needed at the lower temperature, and uneconomical to use it. A single class of insulating materials need not be used in every part of the complete insulation system.

2. The temperature capability of a given material is influenced strongly by the environment to which it is exposed. Hence, the temperature capability of a material should be defined in terms of the conditions under which it is tested. To take an extreme case, an insulating material exposed to an atmosphere that would degrade it chemically in a very short period of time has no value as insulation in that atmosphere at any temperature. The same insulation might be rated for 200°C service under different environmental conditions. No single temperature limit can describe the temperature capability of a given material under every ambient or operating condition.

3. In addition, the temperature at which a material is operated depends upon the required life of the equipment. Equipment that is designed to last a short period of time can use insulation at higher temperatures in order to get an appropriately economical design.

2.3.4 MANUFACTURING PROCESS

The manufacturing of coated wire and cable is a multi-stage process. Raw materials are combined in a series of manufacturing steps including resin and additive manufacturing; resin compounding, wire drawing, or fiber optic, extrusion, cabling, and jacketing.

Polymers and additives are combined together in a compounding operation to produce materials formulated to meet the various insulation or jacketing performance requirements e.g., heat and light stability, smoke retardancy, or water resistance. Once the additives have been combined with the polymer resin, the resulting material typically goes through re-heating and cooling to produce small, hard pellets. These pellets are later re-melted in extrusion equipment to insulate or jacket wire and cable.

The core of the product is a metal, usually copper or aluminum rod or fiber optic preform that is drawn down to a specified diameter. The process of “drawing” wire involves reducing the diameter of the core by pulling it through a converging set of dies until it reaches the specified size. Some products then require various drawn wires to be bundled together. Fiber optics uses a different process involving an atmospheric controlled furnace to melt the preform and draw it to the specified diameter.

Plastic compound is then extruded over the core to provide jacketing or insulation. When plastic covers bare electric wire, the coating is called primary insulation. A secondary layer of plastic extruded over a wire or a group of wires is called a sheath or jacket.

Extrusion is the process of melting, feeding, and pumping a polymeric compound through a die to shape it into its final form around the wire. Depending on the desired performance characteristics, the insulated wires are often combined, or cabled, in various configurations. A critical requirement is that the melt leaving the die is very uniform. Another critical requirement is that the line must be capable of running the wire or cable with uniform tension at a desired but constant speed without variation or drift.

Wire and cable coverings are tested in-line generally more than any other extruded product because they are rather inaccessible for many tests when wound on a reel. Spark testing is very common. The wire passes through a high-voltage field, and if there are any breaks, pinholes, or thin spots in the covering, a circuit is completed to the conductor and a signal of some type is produced. In addition, some measurements are made to ensure conformance to specifications. Finally the cable is wound onto reels and shipped to a job site or retailer.

There are several electrical cables manufacturers in Saudi Arabia supplying the markets need in Saudi Arabia, Middle East and some abroad world countries. The following are some of these manufacturers.

2.3.4.1 JEDDAH CABLE COMPANY (JCC)

Founded in 1988 as a subsidiary of Elsewedy Group International (SGI), which was established in the late 40's in Egypt. JCC is the manufacturing arm of El Sewedy establishment (ESE), which began its electrical distribution business during the early 60's in the Kingdom of Saudi Arabia. From a one plant beginning JCC has now grown to 5 plants exporting to 15 different countries, employing 700 people.

JCC produce indoor wires 300/300 volt or 450/750 volt, copper conductor PVC insulated. The low voltage cables rated 0.6/1 KV are PVC, XLPE or PE insulated with copper or aluminum conductor. Their products include medium voltage cables up to 36 KV, XLPE insulated, and overhead lines. They are producing PVC compound for electrical cables, mater batches, soft and rigid profiles, etc. [20]

2.3.4.2 SAUDI CABLE COMPANY GROUP

The Saudi Cable Company (SCC) was founded in 1976 and currently based in Jeddah. It is the first cable manufacturer established in the Arabian Gulf, and remains one of the largest cable manufacturers in the region. Originally founded in 1975 as a joint venture solely between Xenel Industries and Anaconda. The company shares are now listed on the Saudi Stock Exchange.

SCC Group produces a wide range of conductors and cable products, and is integrated vertically upstream into copper rod and PVC, and downstream into turnkey projects, from design and installation to testing and commissioning. In addition to local sales, SCC has successfully exported to over 40 countries worldwide. [21]

2.3.4.3 RIYADH CABLES GROUP OF COMPANIES

Riyadh Cables Group of Companies (RCGC) is one of the leading and largest cable and allied manufacturing industry in the Middle East. Ever since its establishment, RCGC has pioneered the cable and wire industry in the Middle East and is the leading manufacturer and exporter of all kinds of power and telecommunication cables for demands made upon electrical, mechanical and thermal qualities. With a 1993 paid up capital of SR 868 million, a dedicated and professional staff of over 1200 employees and modern production facilities of over 260,000 M2, located in Riyadh's second industrial city, they are now in a solid position for further expansion.

The wide product range of RCGC includes small PVC insulated building wires rated 300/500 Volts up to and including 230 kV XLPE insulated high voltage cables with a variety of special features to suit market needs. Overhead line conductors, communication cables used in telephone and information networks from one pair to 3600 pairs with advance characteristics and components. They produce fiber optic cables, co-axial cables, copper rods, PVC granules, wooden and steel drums, etc.

Also included in the product range are categorized cables to be used in industrial plants, power stations, multi-storied buildings, hotels, subways, vehicular tunnels where demands are made on flame retardancy and reduction of density, toxicity and corrosivity of smoke i.e., Low Smoke and Fume (LSF), Halogen free cables. Fire retardant cables to IEC 332-1, IEC 332-3A, IEC 332-3B and IEC 332-3C, PVC sheathed cables which are anti-termite, anti-rodent, ultraviolet resistant, oil resistant and cables with special sheathing materials such as CPE, LDPE, LLDPE, MDPE and HDPE are also available upon request. The product range is also inclusive of special watertight cables, which have been manufactured and supplied in huge quantities both home and abroad. [22]

CHAPTER # 3

BREAKDOWN CHARACTERISTICS AND ELECTRICAL AGING OF CABLE INSULATIONS

3.1 INTRODUCTION TO DIELECTRIC BREAKDOWN PHENOMENA IN CABLE INSULATIONS

The main stress for insulating materials is the electrical one, because voltage is always applied to them. However, insulation is usually exposed to multi-stress conditions: such as, high temperatures, pollution, humidity, radiations, vibrations and so on. Even when other stresses have a much greater effect than the electrical gradient, failure is still due to electrical breakdown. This occurs when electric strength, because of aging, decays to the value of the applied electrical gradient. Decline of electric strength is due to all the stresses acting on the material which are the cause of its aging. Aging can be evaluated through measurement of the electric strength decrease. This can be carried out on specimens of materials or laboratory models, because it is a destructive measurement.

Great strength does not necessarily correspond to great endurance;

therefore, a material having high electric strength can rapidly become a bad-insulating material even when not exposed to very high stress.

3.1.1 DIELECTRIC BREAKDOWN STRENGTH

The measured values of the breakdown voltage V_B of solid dielectrics are greatly influenced by the experimental conditions. For example, when voltage is applied to the solid specimen kept in a surrounding medium of liquid or gas, a partial discharge in the surrounding medium often occurs mainly at the edge of the electrode before a complete breakdown of the solid dielectric. This phenomenon influences V_B of solid and decreases it, and is called the edge effect. In order to eliminate this effect, special forms of specimens and electrodes have been developed [23-27]. If electric strengths $F_B = V_B$/sample thickness of some typical polymers are measured carefully with dc voltage to eliminate the edge effect [23-32], the following characteristic results were confirmed.

(a) The electric strengths of polymers are in the range of 1 to 9 MV/cm at 20°C.

(b) In general, the maximum values of the electric strengths of polymers are obtained in the low temperature region.

The highest electric strength ever obtained for polymers is 15 MV/cm at -190°C for polyvinyl alcohol.

3.1.2 TEMPERATUTRE DEPENDENCE

Physical properties of polymers change with temperature, accordingly the temperature dependence of their dielectric breakdown is of prime importance in analyzing their breakdown mechanisms. In general, the temperature dependence of the F_B of polymers is roughly divided into the following two regions.

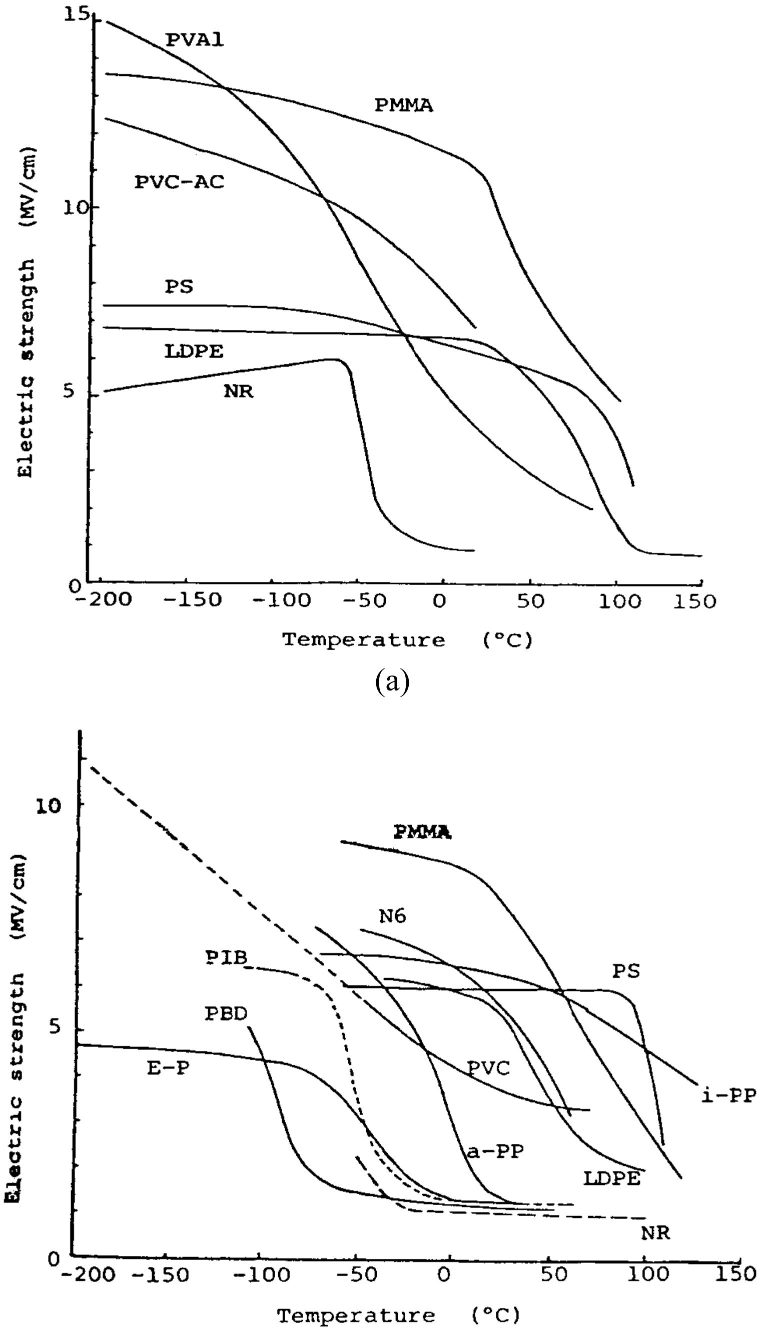
(a) Low temperature region: $\partial F_B / \partial T \approx 0$, T = Temperature. In this region, F_B increases slightly with increasing temperature or F_B is almost independent of temperature.

(b) High temperature region: $\partial F_B / \partial T < 0$, in this region, F_B decreases with rising temperature.

The temperature dependence for F_B of many polymers listed in Table IV is shown in Figures 3.1-a and 3.1-b. The breakdown characteristics shown in Figure 3.1 are classified into two types. For non-polar polymers, there clearly exist low and high temperature regions. However, for polar polymers, as temperature rises, F_B decreases from an extremely low temperature (-200°C) to some critical temperature (T_c) from which F_B falls steeply. Thus, clear low temperature region for polar polymers does not exist.

TABLE IV: MORPHOLOGICAL FEATURES of TYPICAL POLYMERS.

Polymer	Features	
Low density polyethylene (LDPE)	Non-polar	Crystalline
High density polyethylene (HDPE)	Non-polar	Crystalline
Polystrene (PS) (atactic)	Non-polar	Amorphous
Atactic Polypropylene (a-PP)	Non-polar	Amorphous
Isotactic Polypropylene (I-PP)	Non-polar	Crystalline
Ethylene-propylene copolymer (E-P)	Non-polar	Amorphous
Polyisobutylene (PIB)	Non-polar	Amorphous
Polyvinyl alcohol (PVAL)	Polar	Crystalline
Polyvinyl chloride (PVC)	Polar	Amorphous
Polymethyl methacrylate (PMMA)	Polar	Amorphous
Polyvinyl chloride-acetate copolymer (PVC-Ac)	Polar	Amorphous
Ethylene-vinyl acetate copolymer (EVA)	Polar	Crystalline (amorphous)
Polybutadiene (PBD)	Non-polar	Amorphous
Poly 1,4-cis isoprene (NR)	Non-polar	Amorphous
Nylon 6 (N6)	Polar	Crystalline
Polyethylene terephthalate (PET)	Polar	Crystalline, Amorphous
Polycarbonate (PC)	Polar	Crystalline



(a)

(b)

Figure 3.1: Examples of the temperature dependence of electric strength of polymers.

3.1.3 TIME DEPENDENCE

In general, dielectric breakdown occurs some time after the voltage application. This time delay for the breakdown varies from a very short time, about 10^{-9} sec, to a very long time, more than several hours, depending on the breakdown mechanism.

3.1.4 DIELECTRIC BREAKDOWN

The first breakdown theory of solid dielectrics was the thermal breakdown theory presented by Wagner in 1922 [33]. The dielectric breakdown was discussed in terms of the condition to break down the thermal balance between Joule heating due to the conduction current and its dissipation. This theory succeeded in explaining qualitatively the dielectric breakdown phenomena of the practical apparatuses and devices in the high temperature region $(\partial F_B/\partial T<0)$.

However, there exist low and high temperature region in the temperature dependence of electric strengths of solid dielectrics. In the low temperature region, it was difficult to explain the dielectric breakdown phenomena by the thermal breakdown theory. This led to the recognition of the existence of the electronic conduction current in solid dielectrics. The investigations of time lag [34], the direction of the breakdown path [35] and other successive studies

[36,37] suggested that the dielectric breakdown of solids are also due to an electronic process such as the current multiplication by collision ionization of high speed electrons as in gases. Thus, the electronic process was identified as playing an important role in some breakdown processes. Within this framework, a number of different breakdown theories were presented according to differences in the approximation and the energy exchange processes, but the agreement between the theories and the experimental results was not well satisfied.

On the other hand, the breakdown characteristics in the high temperature region have been explained for a long time by the thermal breakdown theory only. The investigation of time lag for the breakdown suggested that the thermal breakdown was not the only breakdown process in this region. However, the theories in the low temperature region were not satisfactory. Proposals were made to modify the collision ionization of electrons with the space charge effect [38] and to consider what role the interaction between the conduction electrons and the electrons trapped in the impurity level plays in the energy exchange process, Frohlich's amorphous theory [39]. The electromechanical breakdown theory [40] was proposed based on the fact that the breakdown characteristics of polymers in the temperature region near the melting point are similar to their mechanical characteristics. This states that the breakdown is caused by the mechanical deformation due to Maxwell stress under the applied electric field. This theory was inherent to polymers and succeeded in explaining the breakdown characteristics of many polymers in the high temperature region. The free volume breakdown theory presented by Artbauer [41], which was taken in explaining the breakdown phenomena of polymers around the glass transition temperature region, was another breakdown theory inherent to polymers. Though many breakdown theories have been proposed, it is still difficult to decide which mechanism plays a dominant role in the breakdown phenomena.

In general, the dielectric breakdown of solids is observed accompanying the destruction of the molecular structure that leads to the transition to conductive material. In order to construct the breakdown theory, the charge carriers and the multiplication process are identified first, and then introduce the breakdown condition into it.

The fundamental breakdown processes are roughly classified into the electronic process and the pure thermal process. Further, regardless of the current multiplication process, there exists the mechanical breakdown process, in which the mechanical deformation under the applied electric field dominates the breakdown phenomena. The summary of the breakdown mechanisms is shown in Table V. When the electric field is applied to the sample, the dielectric breakdown is considered to occur at the minimum value among the electric strengths given by each theory.

The essential feature of the temperature dependence of electric strength

TABLE V: DIELECTRIC BREAKDOWN THEORIES of SOLIDS.

I.	**Electronic breakdown process**		
	Intrinsic breakdown ($\partial F_B/\partial d=0$) d: sample thickness	Theories based on the single electron approximation ($\partial F_B/\partial d\geq 0$)	High energy criterion
			Low energy criterion
		Collective critical field theories	Single crystal ($\partial F_B/\partial d>0$)
			Amorphous materials ($\partial F_B/\partial d<0$)
	Electron avalanche breakdown ($\partial F_B/\partial d<0$) ($\partial F_B/\partial d\geq 0$)	Single avalanche model	
		Collective avalanche model	
	Field emission breakdown ($\partial F_B/\partial d=0$) ($\partial F_B/\partial T=0$)		
	Free volume breakdown ($\partial F_B/\partial T<0$)		
II.	**Thermal breakdown process**		
	Steady state thermal breakdown	($\partial F_B/\partial T<0$)	
	Impulse thermal breakdown		
III.	**Mechanical breakdown process**		
	Electromechanical breakdown	($\partial F_B/\partial T<0$)	

for most linear polymers can be illustrated in Figure 3.2. The temperature range can be classified into three regions. Corresponding to each region, the rheology of the linear polymers and the possible breakdown processes are summarized in Table VI.

3.2 ELECTRICAL AGING

There are essentially two types of purely electrical aging theories and models: those obeying an inverse power law and those described by an exponential decay at high fields. It is important to stress that these theories are mostly derived from empiricism. A comprehensive theory based on the physics of failure has yet to be done.

3.2.1 INVERSE POWER LAW

It has been empirically observed [42-48] that, over a restricted time scale the lifetime t of many dielectrics subjected to high field F varies according to

$$t = CF^{-n} \tag{3.1}$$

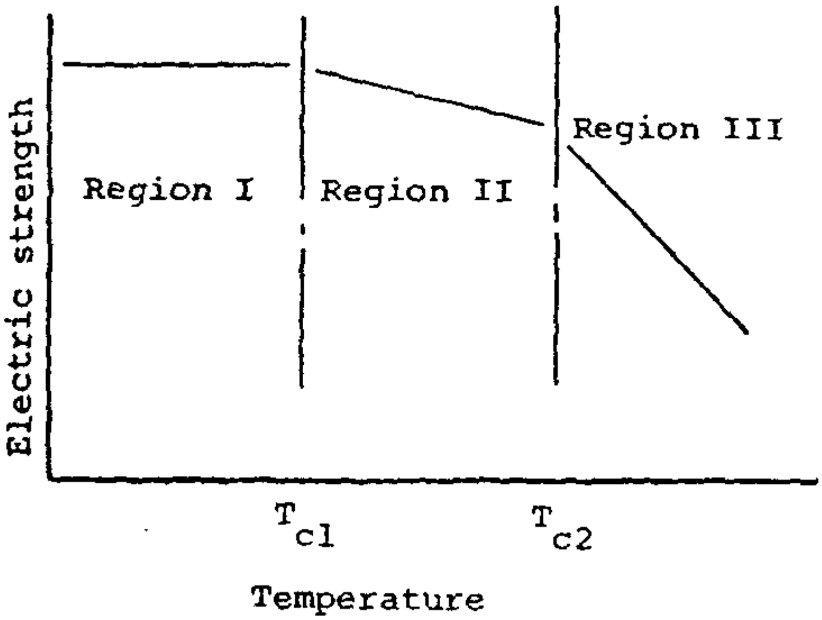


Figure 3.2: Outline of the temperature dependence of electric strength of linear polymers.

TABLE VI: CORRESPONDING BREAKDOWN PROCESSES for REGIONS I, II and III in FIGURE 3.2.

Region	**Molecular state**	**Corresponding breakdown process**
I	Glass-like	Electron avalanche breakdown
II	Rubber-like	a) Collective breakdown for amorphous dielectrics b) Thermal breakdown c) Free volume breakdown
III	Plastic-flow	a) Thermal breakdown b) Electromechanical breakdown

where C and n are adjustable parameters varying with the experimental conditions. Kiersztyn [49] derived similar equations with more variables but no verification of his model has ever been attempted. Thus, voltage endurance results plotted on log F vs. log t plots should yield a straight line of slope n, Figure 3.3. Such life curves have become extremely popular and most of the results presented in the following section were originally plotted on log - log graphs. It is possible to establish a correlation between the power law and the Weibull distribution [49-52]. It is also well known that high frequency measurements yield shorter lifetimes (at least up to 5 kHz). The influence of frequency f can be included in equation (3.1) [52] to give

$$t = CF^{-n} \quad f^{-x} \tag{3.2}$$

where x is a constant. It is speculated that the failure mechanism does not change with frequency. Values of the constants n and x were given in [52].

The inverse power law has several limitations. It has no clear physical basis and at least two adjustable parameters of unknown origin. Almost any kind of results will give a straight line on log-log graphs, especially over a restricted range of values.

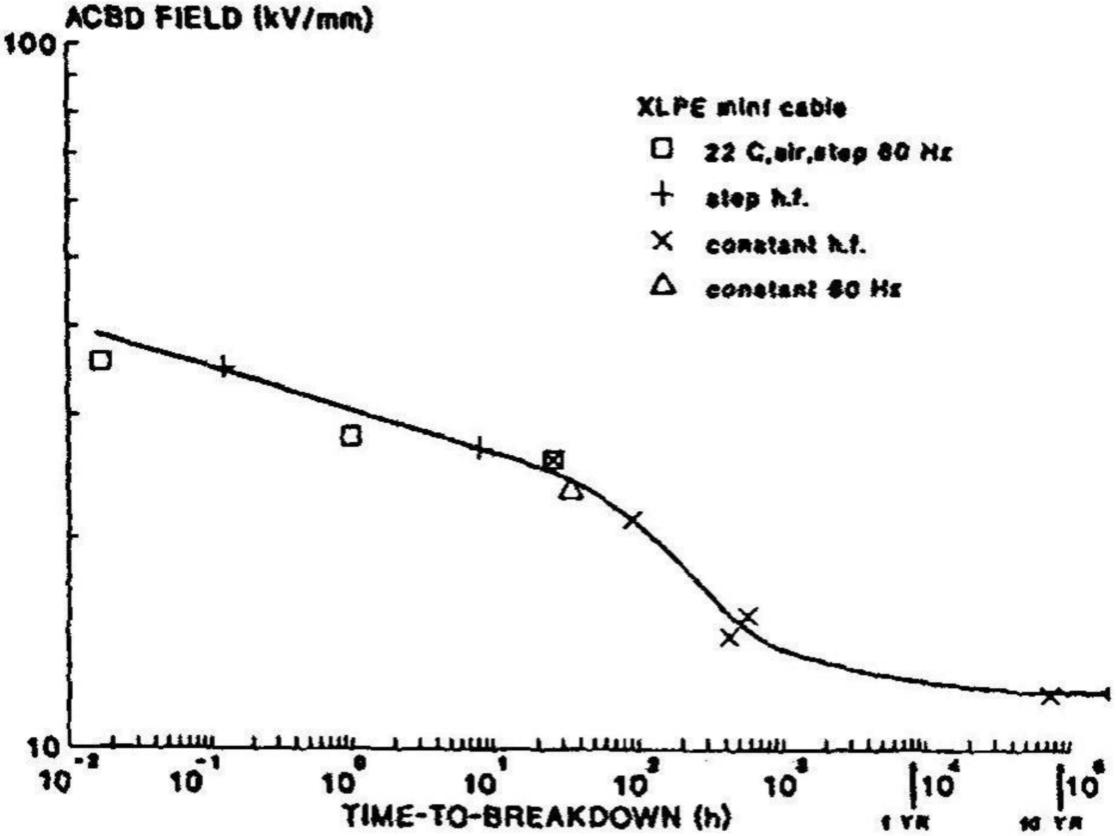


Figure 3.3: Log field vs. log time representation of XLPE cables aged in air at 22 °C under various conditions.

It tends to give optimistic lifetime predictions for service conditions extrapolated from high field laboratory experiments. It cannot predict the influence of water and temperature directly. When results are obtained over a large range of fields and times, there is sometimes up to three different straight lines. In such case, it is evident that extrapolations made at high fields cannot readily describe service conditions.

Bahder *et al.* [48] used the inverse power law to interpret the voltage endurance measurements of XLPE cables, Figures 3.3, 3.4. From the observed change of slope at low fields, they concluded that a state of nearly infinite life exists below a threshold field. However, results obtained by others [50] or with other dielectrics reveal that in the third regime the breakdown voltage continues to decrease with increasing time.

In order to be able to describe the change of slope observed in Figure 3.3, Bahder et al. [48] proposed a modified version of the power law. They suggested that discharges in voids cause electric charges to penetrate into the dielectric, at least near the void surface, which agrees with McKean *et al.* [53] who observed a crude correlation between micro-voids size and breakdown voltage under very high stresses (40 kV/mm). According to Bahder *et al.* [48], the charge gradient varies exponentially which leads to a charge flow rate Q given by:

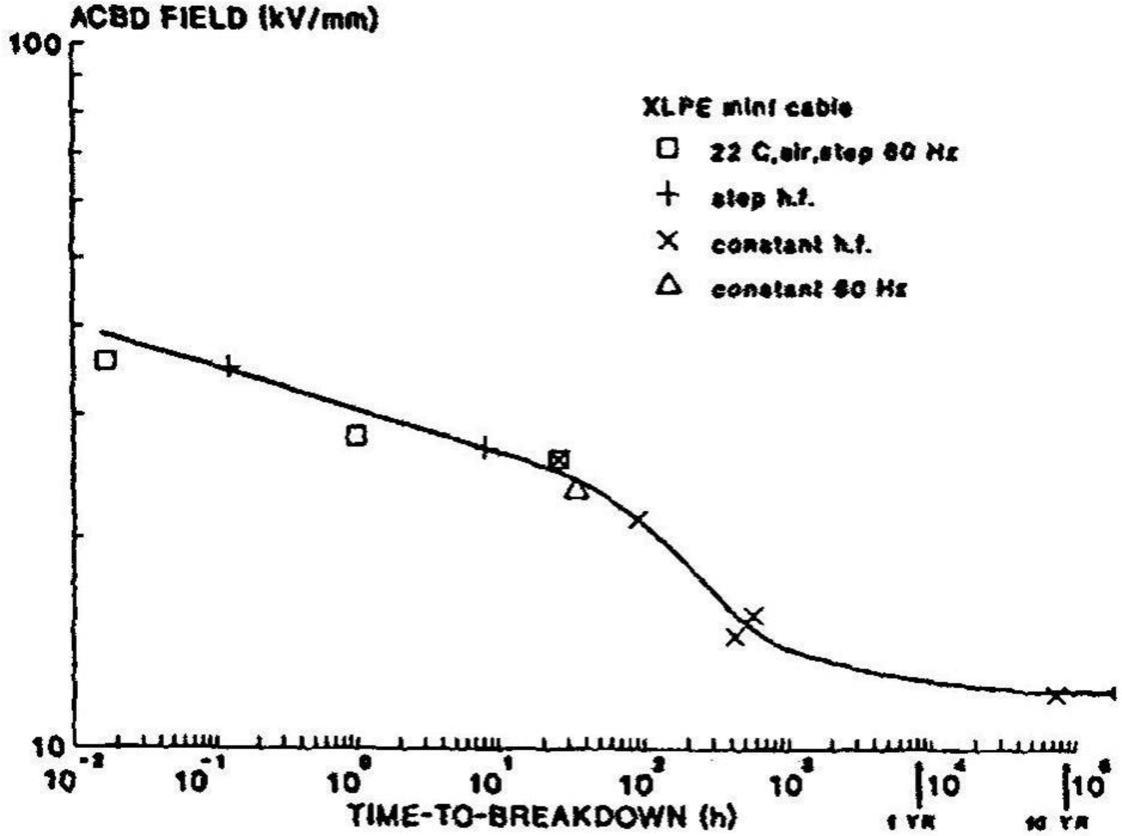


Figure 3.4: Miniature XLPE cables aged in air at various temperatures.

$$Q = 120ta_3 \quad \{\exp[a_4(F - F_o)] - 1\} \tag{3.3}$$

where a_3 and a_4 are constants and F_0 is the onset field required for discharges. Discharges induce some channel erosion leading to breakdown when craters with a critical length are formed. The time to breakdown is given by

$$t = \{fb_1 \exp[b_2(F - F_o) - 1](\exp[b_3 F_b] + b_4)\}^{-1} \tag{3.4}$$

where f is the frequency, b_1, b_2, b_3 and b_4 are constants, and F_b is the residual electric strength of the dielectric [48]. Although this may be considered as a step in the right direction, this very cumbersome equation nevertheless has many unknowns.

It should be noted that the apparent threshold voltage shown in Figure 3.3 disappears or becomes much less evident when results are plotted on a *F vs. log t* graph. Therefore, it seems that the inverse power law equation (3.1) does not offer a very good description of the electrical aging of extruded cables over a long time span.

3.2.2 EXPONENTIAL DECAY MODELS

Dakin [54,55] has proposed that voltage endurance is governed by an exponential decay equation such as

$$t \quad \alpha \quad \exp\left[\frac{E - bF}{kT}\right] \tag{3.5}$$

where E is the activation energy of the process and b is the slope in a log t vs. F plot. However, it was soon recognized that the simple exponential relation predicted by this equation can not describe very long time experiments. Dakin and Studniarz [56] therefore suggested adding a 'tail' to the exponential decay to describe long lifetimes. As shown in Figure 3.5, the tail is the regime where results do not obey an exponential law and where the breakdown field value changes very slowly with aging time. The main assumptions in the Dakin theory can be summarized as follows.

Breakdown under voltage stress is mainly due to partial discharges, which occur above an onset field F_0; and the rate of degradation is thermally activated, and is therefore characterized by an activation energy E that is reduced, under the influence of field F, by $b\,F$, where b contains the charge and a mean distance

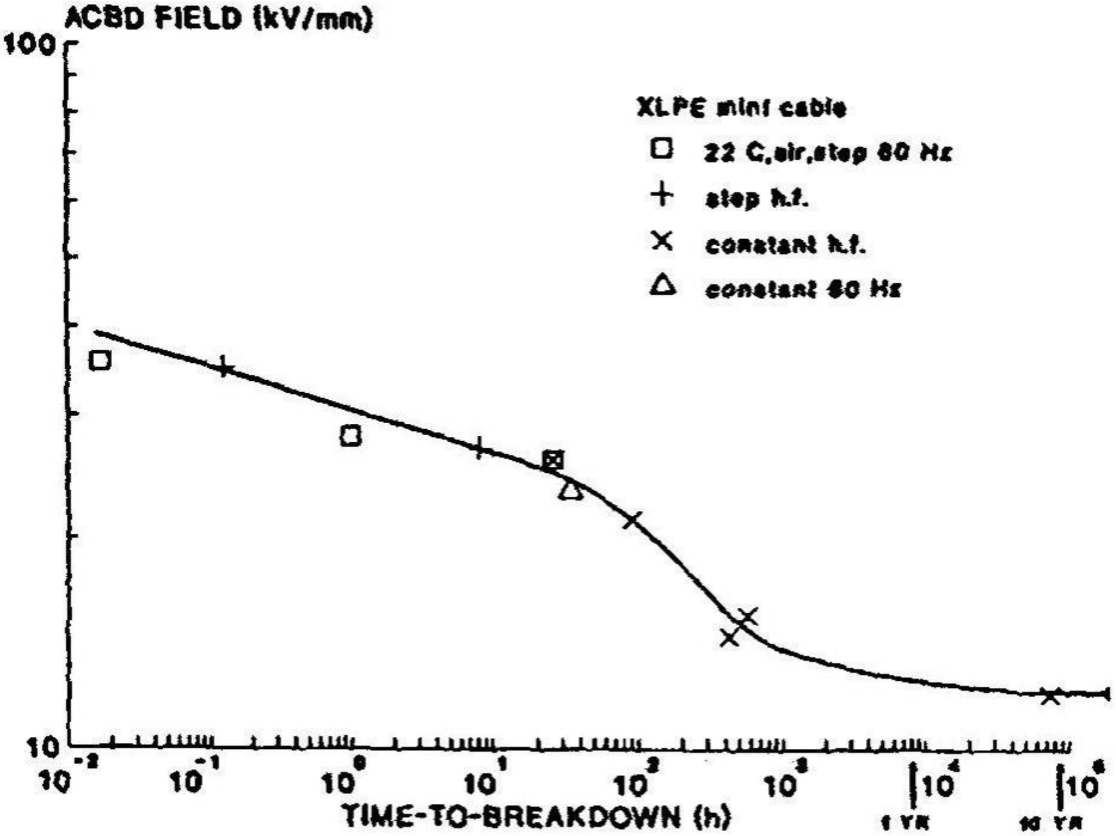


Figure 3.5: Results of Bahder et al. re-plotted on a field vs. log time graph.

parameter.

The time to breakdown at a given frequency f is then

$$t = \frac{(Af)^{-1}}{(F - F_o)} \exp\left[\frac{E - b(F - F_o)}{kT}\right] \qquad (3.6)$$

where A is the fraction of electrons reaching the most critical site [56]. Dakin pointed out as early as 1961 in the Discussion section of [52] that "while the empirical relation between breakdown time and an inverse power of the voltage has been reported by a number of authors to apply to their data, other authors have applied a linear voltage vs. log time empirical relation equally successfully". More recently, Starr and Steffens plotted their endurance results obtained with acrylic sleeves [57] and those of Bahder *et al.* [48] obtained with XLPE cables on both log - log graphs equation (3.1) and on semi log graphs equation (3.6). They concluded that an exponential relation fit the experimental data better than by a power law equation. Figure 3.5 shows the results of Bahder *et al.* Figure 3.3 plotted on a semi log plot; time to breakdown increases exponentially with decreasing field and, at very long times, a tail is visible in agreement with the proposition of Dakin and Studniarz. Identical results are observed when the results of Montanari *et al.* [44] are plotted on a semi log plot, as in Figure 3.6. The model proposed by Bahder et *al.* equation (3.4) should also give a tail in semi log graph but it could not compared with equation (3.5) since it contains so many unknown parameters.

Dakin's theory is very attractive but it suggests that voltage endurance be controlled by partial discharges. Obviously, partial discharges will affect the voltage endurance of a dielectric, especially at high fields, but there are aging cases where no partial charges have been detected [58]. In addition, in purely mechanical breakdown experiments, where partial discharges should not exist, the mechanical life-stress curve of polyethylene is seen to be similar to the voltage endurance curves shown in Figures 3.5 and 3.6. Thus, the exponential decay at high stress seems to apply; to a wide range of applications since it is observed in electrical as well as in mechanical experiments. However, in both cases, a departure from the simple exponential relation is observed at long time, low stress.

Simoni [59] arrived at the same conclusion but, to do so, he used the theory of Endicott *et al.* [60], a modification of the rate theory which predicts that at high stress, electrical or mechanical, lifetime varies exponentially with stress according to [61,62]

$$t \approx \frac{h}{2kT} \exp\left[\frac{\Delta G - e\lambda F}{kT}\right] \tag{3.7}$$

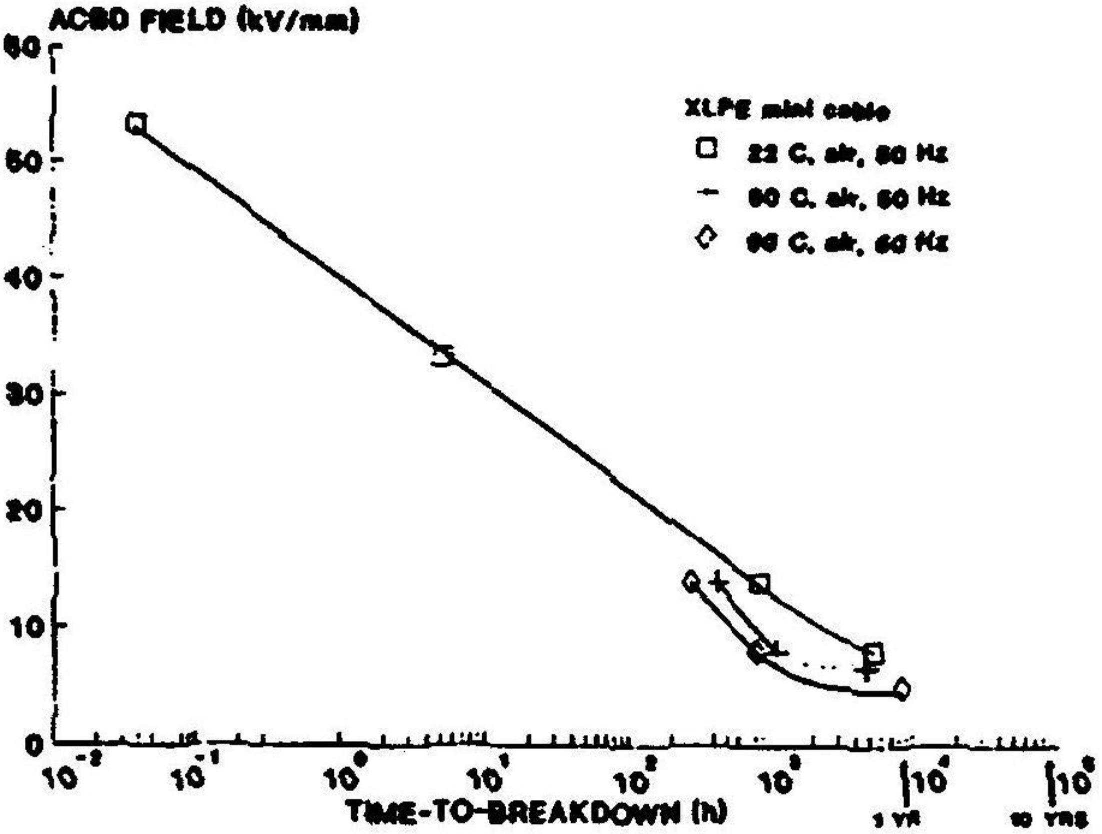


Figure 3.6: Results shown in figure 3.4 re-plotted as field vs. log time.

where ΔG is the Gibbs free energy of the process and λ is equivalent to a scattering length, it is also the barrier width. The two unknown parameters λ and ΔG can be readily estimated from the slope and intercept, respectively, in F *vs.* log t plots, Figure 3.6. In an attempt to give a theoretical basis for the power law equation (3.1), Endicott *et al.* [60] proposed that the Gibbs free energy varies with field according to

$$-\frac{\Delta G}{kT} = \ln F\left(c + \frac{d}{T}\right) \qquad (3.8)$$

where c and d are adjustable constants. A review of Eyring's theory, which employs the Gibbs free energy concept, fails to reveal a derivation of equation (3.8). Simoni and Montanari's simplest equation [43,45] is

$$t = t_o \frac{\exp\left[h^*\left(F_s - F\right)\right]}{\left[\left(F - F_{t_o}\right)/\left(F_s - F_{t_o}\right)\right]^{\mu}} \qquad (3.9)$$

where t_O, h* and μ are adjustable parameters, F_S is the upper limit of the field range where equation (3.9) applies and F_{to} is the threshold field. As discussed in [45], equation (3.9) can become considerably more complex, although its practical interest at that point is not obvious. Montanari and Mazzanti [63] recently published a model that attempts to establish a bridge between Simoni's and Crine's models but it has not the simplicity of the latter.

In fact, the rate theory predicts that the time required to go over the field deformed barrier obeys the following equation [61,62]:

$$t = \frac{h}{kT} \exp\left[\frac{\Delta G}{kT}\right] \operatorname{csc}h\left[\frac{e\lambda F}{kT}\right] \qquad (3.10)$$

which reduces to equation (3.7) at high fields. The *csch* term in equation (3.10) implies that at fields dose to zero, the value of t will tend toward infinity.

Therefore, some sort of tail, i.e. slow decrease of F toward zero at long times is predicted, in agreement with experimental observation. This has some similarity to the Bahder theory with the notable difference that there is no threshold field in this model. In fact, it is unrealistic to expect no aging below a given field when service experience shows that cables break down at very low stress.

CHAPTER # 4

AGING AND CHARACTERISTICS OF PVC AND XLPE INSULATIONS

A material operating under stressing conditions will last more or less according to the magnitude of the applied stresses and material intrinsic qualities. The material properties are functions of time and stress; they do not remain constant but change, making the material worse until it fails. When the material is not able to operate or not operating satisfactorily means it fails. Aging is the progressive decay of the materials' properties and it is the cause of failure.

There are two types of stresses: destructive and non-destructive stresses. The destructive stress is able to destroy the material so that failure corresponds to breakdown, such as the electrical gradient for insulating materials, the mechanical strain, vibrations etc. The non-destructive stresses do not directly produce breakdown but only aging, for example temperature, humidity, radiation environmental pollution and so on. It is necessary to establish a failure criterion, which is a limiting value of material's properties that corresponds to the actual failure of the system in which the material is used.

4.1 DEFINITIONS

4.1.1 AGING

An irreversible change in the properties of materials subjected to stresses of any kind. Aging proceeds in time with a rate depending on the magnitude of the applied stress and can be evaluated at any instance by measuring the basic material properties and comparing their values with the initial ones.

4.1.2 FAILURE

The material in this condition is no longer able to operate and occurs when the material properties decay to a limiting value.

4.1.3 LIFE

The material life is the time until failure condition reached.

4.1.4 STRENGTH

This is the maximum stress, which can be withstood by the material.

Strength is the basic property in the aging process, because failure occurs when strength decays to the value of the applied stress.

4.1.5 ENDURANCE

It is the ability to endure stress. Endurance is not a property that can be measured at a given instant of time, but can be evaluated only by a curve.

4.1.6 LIFE CURVE

It is the graph of life time vs. the corresponding applied stress. If this line is straight, not curved in an appropriate co-ordinate system, then the endurance evaluation can be made.

The basic property of insulating materials is the electric strength, which is the magnitude of the electrical gradient above which breakdown occurs.

4.2 THE BASIC PROPERTY OF MATERIALS

Strength is a basic property in destructive stress, whose comparison with stress allows a non-arbitrary criterion to be established, which can be measured by an increasing stress up to breakdown. Because of the inevitable differences between specimens of the same material, the test must be carried out on a batch of specimens and the results are statistically elaborated in order to obtain the most consistent value for strength. Moreover, it is necessary to specify the test conditions, such as, the shape and size of the test cells, environmental conditions, methods of increasing stress and so on. All these are problems of strength measurements.

In service, the material will have a value of strength higher than the applied stress. When this value has dropped to that of stress, because of aging, does the material fail. Therefore, the strength equal to that of the applied stress gives the failure criterion in the case of destructive stress. However, if overstresses occur, they can reach the value of strength even if aging has not yet taken place in the material. In addition, the ability to withstand overstresses may depend on their type and may be different from their ability to resist service stress. It is well known that electric strength of insulating materials (dielectric) changes according to the type of voltage, a.c., d.c. or impulse.

4.3 ENDURANCE AND ITS EVALUATION

The effect of a stress applied on a material is a progressive decline of its properties down to failure. The higher the stress, the earlier the failure and thus the shorter the material life. This effect can be described by means of a basic curve, which is called the life curve of the material for that particular kind of stress. By plotting times to failure vs. the corresponding values of the applied stress, the life curve is obtained.

The life curve shows a decreasing trend having a slope closely correlated to the system endurance. Therefore, the longer the life at the same stress the greater the endurance, while a steep slope of the curve characterizes a system having scarce ability to endure stress. This becomes more evident if the relative value rather than the absolute values are considered for stresses and the initial strength of the materials is taken as the reference, Figure 4.1. In this way, the comparison between materials from the point of view of their endurance is better, because all curves for every material start from the same point and their difference in initial strength is ignored. If the line is straight, its slope is constant and can be taken as endurance evaluation. Therefore, endurance can be evaluated by a coefficient, which is the reciprocal of the slope of the life-line in an appropriate coordinate system. This coefficient is called endurance coefficient.

4.4 BASIC FORMULAS FOR SINGLE STRESS

If A means aging, S a generic stress, t time, and $p = P / P_0$ a property related to failure, whose variation down to a limiting value p_L is the cause of failure, then the general relationship between aging, time, stress and property is:

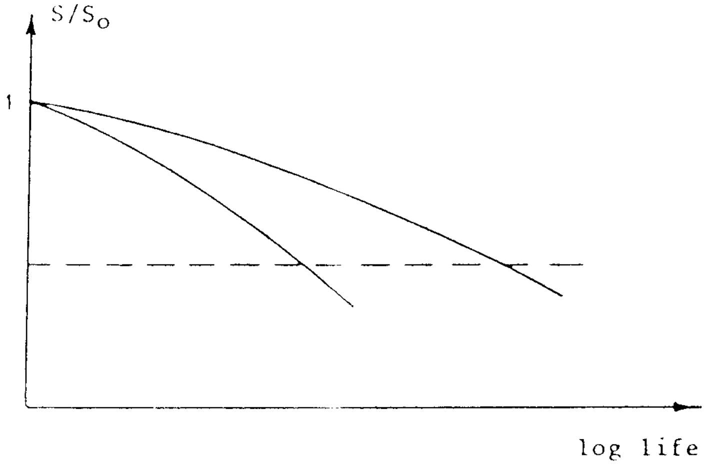


Figure 4.1: Normal endurance line.

$$A = f(p) = \int_0^t R(S) \, dt \tag{4.1}$$

Where, $R = \frac{dA}{dt}$ is the aging rate.

If stress is constant the general relationship is reduced to:

$$A = f(p) = R(S) \, t \tag{4.2}$$

Failure occurs when p decays to the limiting value, and time becomes life, L. Correspondingly, aging reaches its maximum value, A_L:

$$A_L = f(p_L) = R(S) \, L \tag{4.3}$$

Equation (4.3) is the life equation of the material under stress S; it can be written as:

$$L = \frac{f(p_L)}{R(S)} = F(S) \tag{4.4}$$

Which represents the life-line of the material under that kind of stress. The surface represented by equation (4.2), that relates the three variables: stress, time and property, is the aging or time-behavior surface of the material, whose intersection with the failure plane p_L is the life-line of equation (4.3).

Electrical gradient, E, is the main stress for insulating materials, and the most significant property is the electrical strength, ES. In this case, equation (4.2) can be rewritten as:

$$A = f\left(\frac{ES}{ES_o}\right) = R(E) \quad t \tag{4.5}$$

The failure occurs when ES decays to E. A certain time is necessary to puncture the material, although it is very short but not instantaneous.

The ES test is carried out by an increasing voltage, and breakdown occurs after a time t_p , which is the time to breakdown with progressive stress. It is longer than time t_o, which is necessary to puncture the same specimen by keeping the breakdown voltage on it constant. By considering a constant stress in the above relationships then, t_o is the time to failure, which must be combined with the initial electric strength ES_o. When an electrical stress equal to electric strength is applied, t_o is the time necessary to give rise to breakdown at constant stress. Once failure has taken place, the insulating material is punctured and its electric strength is reduced to 0. Therefore, the limiting value for electric strength is 0. Putting this value into equation (4.5), it becomes:

$$A_L = f(0) = R(E) \quad L \tag{4.6}$$

This is the equation of electrical life in general form. If equation (4.2) is divided by equation (4.3), it results in:

$$A = A_L \frac{t}{L} \tag{4.7}$$

This quantity varies from 0 to A_L, which is a characteristic quantity for each material. This line, which is introduced as the plot of times to failure vs. the corresponding values of stress, is defined as the intersection of the aging surface with the failure plane.

4.5 LIFE AND AGING TESTS

Life tests are normally carried out to assess endurance of insulating materials. They consist of exposing specimens of the insulating material to constant stress until they fail. The time to failure in operating conditions should be predicted from a statistical point of view from these tests. Since this result must be obtained in times much shorter than the expected life in service, the tests are performed in heavier conditions than the operating ones. These are called accelerated life tests, which require extrapolation to achieve their aim.

In order to assess the present state of electrical apparatus and to predict their future behavior, tests in service could be performed. These are diagnostic tests, non-destructive, based on measurements of some quantity related to aging if it exists.

Diagnostic tests are aging tests, not life tests. Aging test is a test, which is carried out on specimens, aged without waiting for their failure. Such aging tests are the measurements of properties, even destructive, which are made on specimens subjected to thermal aging at time intervals so that the trend of the property changes in time can be detected and the time to reach the end point determined. Aging test becomes a life test when the time of exposure to temperature becomes so long that the property decays to or below the end point, this means that failure has occurred. It can be noticed that a life test always involves aging whereas an aging test does not necessarily involve failure. Furthermore, the main feature of a life test is to measure the time to failure. While in the aging test, is to measure the changes in the physical properties of the material structure caused by aging.

4.6 CAUSES OF AGING

The aging process of insulation in cables, capacitors rotating machinery, transformers, electronic systems, etc., differs in each system because of the different utilization and stress conditions. Temperature is not the only or the most dominant factor, however it is the most frequent cause of insulation aging. Electrical equipment has been known to fail by voltage stress, by mechanical stress, by environmental conditions of heavy humidity, or chemical contaminants, etc.

Boulter [64] asserts that while thermal endurance may be the predominant factor in determining the rating of smaller and lower voltage machine insulations, it is unrealistic to expect the same to be true in larger machines. In high voltage machines, Boulter stated that voltage effects are more important. Corona endurance and dielectric properties take on added significance in determining machine rating. Also, electromechanical forces become major design considerations in large machines, in which may be neglected in small machines. In addition, the operating environment plays a large role in determining insulation life and machine rating. Thermal aging for most materials is quite different in the dry hydrogen gas atmosphere used in large generators than it is in smaller air-cooled units.

However, the main stress for insulating materials is the electrical one, because voltage is always applied to them. Even when other stresses have a much greater effect than the electrical gradient, failure is still due to electrical breakdown. This occurs when electric strength, because of aging, decays to the value of the applied electrical gradient. Decline of electric strength is due to all the stresses acting on the material which are the cause of its aging.

4.6.1 THERMAL AGING

The direction of work should now turn to measuring the degradation near or at operating temperature for a relatively brief period of time, in hours or days, and integrating the differential changes over the expected life. Paloniemi [65] proposed a technique using Isothermal Differential Calorimetry. Kelen [66] acknowledges a potential drawback of accelerating aging because of the risk of changing the aging mechanism from that operating under normal service stress.

4.6.1.1 THERMAL AGING AND EFFECTS ON CABLE INSULATIONS

When electrical insulation, organic materials in particular, exposed to elevated temperatures are subject to deterioration. Deterioration produces changes in the physical properties of materials so that they become unable to meet their functions after a certain time, this means failure. The limiting value, P_L, is the value of properties, which below the material is no longer able to operate satisfactorily.

Therefore, thermal stress can produce failure without destroying the specimen, and for this reason the limiting value is established according to a criterion, which must take into account the function that the material is expected to meet in service. Since the rate of deterioration increases rapidly with rising temperature, which causes an acceleration of the chemical reactions occurring in materials, therefore, it is necessary to limit the temperature to ensure long life of electrical equipment. Because thermal behavior of materials considerably changes from one material to another, insulating materials have been classified according to the maximum temperature they are able to endure for a satisfactorily long period of time. This classification was made on the basis of the chemical nature of materials. Subsequently, the ever-increasing number of synthetic materials and their combinations has brought out a different classification based on tests besides experience.

In Japan, the thermal aging of materials was probably taken up for the first time in 1910 [67]. Thermal aging is affected by the concentrations of oxygen and products in the reaction region. In 1925, Kujrai and Akagira reported that in the accelerated aging test, there is a linear relationship between the logarithm of the time required for the characteristics to decrease to a certain level and the reciprocal of absolute temperature [68]. After issuing the report, Akahira devoted himself to the kinetic development of the thermo gravimetric analysis, in which the mass change of a substance with the thermo balance is measured while increasing the temperature at a constant speed [69]. From 1927 to 1929, he recorded pioneer achievements in this field and these results were adopted in recent short-time thermal endurance testing method by thermal analysis. The relationship between temperature and weight change became possible to be measured and was investigated [67].

In 1930 to 1945, the development of insulating materials was stagnant where electrical appliances were diversified and made progress [67]. After 1950, as the materials were diversified and the electrical appliances were made smaller and better in performance through the development of the molecular industry, the importance of the thermal endurance test was recognized and the number of reports concerning thermal aging and thermal endurance of various materials increased. The committee on deterioration for organic materials was established in 1953 in the Institute of Electrical Engineers of Japan (IEEJ) and an investigation was started on the thermal endurance of various insulating materials and testing methods. In 1957, the Committee issued survey reports on the worldwide tendency of thermal rating, thermal endurance testing method of materials, and thermal resistance evaluation tests for equipment insulation [70].

The international coordination of standards, accumulation of comparison data among various characteristics and testing methods accompanying the diversified types and applications and development of practical testing methods have become important subjects.

The equipment used in thermal aging of the insulating materials proceeds, in many cases, under changing temperature. The theoretical treatment when the reaction proceeds while temperature changes, was made by Akahira [69]. He showed an equation for conversion to constant temperature expressing the same reaction rate in the same time as the changing temperature. In the method of calculating a representative pattern of temperature change, which was reported by Ozawa, the integrated value of the reaction rate formula assumed remains constant independent of the pattern of the midway temperature change, and assuming that the initial state of deterioration and the ultimate state are the same [71]. The integrated value has the unit of time corresponding to the service life and it is called reduced time.

Takahashi reported that the characteristic changes at different testing temperatures can be connected and showed on one master curve by measuring the change of rigidity modulus as the varnish glass is heated and processing by the concept of reduced time [72]. Furusho reported the possibility of the same treatment for thermoplastic [73]. It is possible to detect the temperature at which the aging reaction changes and to predict the characteristic change at unknown temperatures through such data processing. Kaneko and Sudo conducted thermal aging tests under conditions where the temperature repeatedly rises and falls linearly within a fix temperature range [74]. They reported that as the number of heating and cooling cycles increases, the deviation from the equivalent temperature and reduced time increases and that the accumulation of the internal strap caused by temperature change accelerates the deterioration. Yamamoto reported that as the varnish hardens the same effect increases [75].

The distribution of oxygen concentration in the thickness direction based on the ratio of diffusion constant and reaction rate constant in the unilateral diffusion in a solid of infinite distance can be obtained by the equation introduced by Osuo [76]. From the equation it is possible to introduce the weight decrease rate on the surface of the specimen and to estimate the deterioration tendency of the material, independent of the thickness. Hino introduced an equation to apply the same idea to the unilateral diffusion of finite thickness. Sudo, on the other hand, reported that the reaction proceeds in such a form that the reaction interface moves from the surface into the material proportionally to the square root of time [77]. The Investigation Committee of Thermal Endurance Test Method on Insulating Materials of IEEJ conducted joint tests using varnishes with different film thicknesses and found that the weight reduction of many varnish films is linear with the square root of time [71].

The need to produce a unique, significant thermal endurance graph, related to actual failure, leads one to select electric strength as the reference property on which the thermal endurance characterization is based [78]. The other properties measured for thermal aging evaluation, e.g. weight and tensile modulus, should then be referred, for end-point selection, to electric strength.

The available methods for thermal endurance characterization of insulating materials are the conventional procedures and the analytical test methods [78]. Other methods have been used similarly to the analytical test methods with the main objective to reduce test times without losing accuracy and practical significance of the results. These are thermo-gravimetric analysis [79-81] and relaxation measurements [82].

4.6.1.2 THERMAL LIFE EQUATION

Since thermal deterioration is due to the acceleration of chemical reactions produced by increasing temperature, the aging rate can be assumed proportional to the rate of chemical reactions. Therefore, aging rate dependent on temperature according to the following relationship known as the Arrhenius law [83]:

$$R = R^{'} \exp\left(-\frac{W}{KT}\right) \tag{4.8}$$

Where W is the activation energy, K Boltzman's constant and T the absolute temperature (T = 273 + θ). The material life, that is the time to reach the failure criterion, is derived from equation (4.2):

$$L = \frac{A_L}{R} \tag{4.9}$$

Hence:

$$L = L^{'} \exp(B/T) \tag{4.10}$$

Where $B = W / K$ and L' is a constant for the material under consideration that equals the life of material when temperature tends to infinity.

According to equation (4.10), L becomes infinite only at absolute zero temperature, because only at that temperature chemical reactions are ceased. However, if a material is kept at room temperature without any stress applied, including environmental ones, its life is practically infinite. Therefore, it is useful to introduce life at room temperature, L_o, into equation (4.10), instead of L' which has no practical interest. Therefore:

$$L_o = L' \exp\left(\frac{B}{T_o}\right) \tag{4.11}$$

Where, T_o is the absolute room temperature, it follows that:

$$L = L_o \exp(-B \quad cT) \tag{4.12}$$

Where,

$$cT = \frac{1}{T_o} - \frac{1}{T} = \frac{T - T_o}{TT_o} \tag{4.13}$$

is the conventional thermal stress. The conventionality is derived from choosing the room temperature as the reference. It must be emphasized that the definition of conventional thermal stress is not arbitrary. The thermal aging rate depends on $-1/T$ and not on T, thus thermal stress (cT) must be a quantity variable according to $-1/T$, and it is positive. Practice suggests room temperature because the life tests for stresses, other than the thermal stress, are usually carried out at room temperature.

cT is 0 at room temperature, therefore, only temperatures higher than that are considered to produce deterioration. cT is plotted against temperature as shown in Figure 4.2. The curve, which is a hyperbole, increases up to a maximum value equals to $1/T_o$ when temperature tends to infinity. The values of cT at the experimental test temperatures T_1 = 130°C, T_2 = 170°C and T_3 = 220°C, are shown on Figure 4.2. At temperatures lower than room temperature, T_o, cT becomes negative and life becomes longer than L_o.

Equation (4.12) is a new way to express thermal life and this expression will be used as the thermal life model.

4.6.1.3 THE ARRHENIUS GRAPH

By taking the logarithms of both sides of equation (4.12), this becomes:

$$\ln L \quad = \quad \ln L_o \quad - \quad B \quad cT \tag{4.14}$$

Plotting $\ln L$ vs. cT represents a straight line of slope B. The Arrhenius plot has the logarithm of times as ordinates and the Celsius temperatures, but in a scale

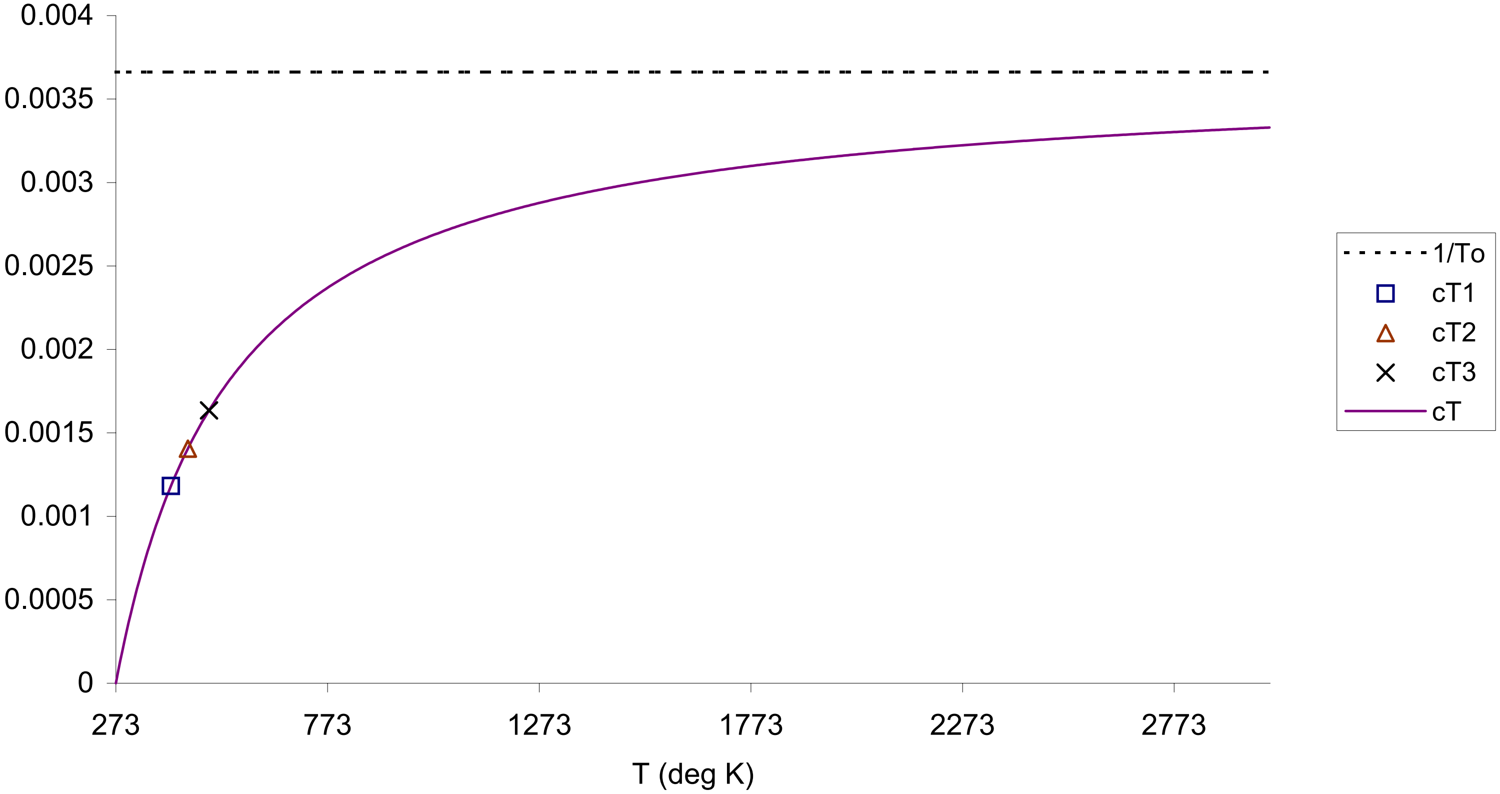


Figure 4.2: Thermal stress as a function of temperature.

proportional to $1/T$, as abscissas.

Such a plot is then appropriate for the thermal life graph by considering either equation (4.10) or (4.12) as the life equation. The only difference is the origin of temperatures, which is T_O in the case of equation (4.12).

Figure 4.3 shows an example of the thermal graph [83]. In comparison with the general case dealt with in Figure 4.1, the thermal life graph is inverted, with lifetimes as ordinates instead of abscissas. In the general case, the endurance coefficient is given by the reciprocal of the slope of the line. However, the thermal endurance coefficient is given by the slope of the line and not by its reciprocal. In this case, the higher the endurance coefficient (B), the higher the activation energy of the chemical reaction involved and hence the greater should be the thermal endurance. This is not evident because any comparison is made in terms of temperature.

In accordance with IEC recommendation 216, insulating materials are classified by means of the “Temperature Index” (TI) [83]. TI is the temperature that corresponds to a time of 20,000 hours when continuously applied to the material to reach the end point. It is not enough to evaluate thermal endurance of materials since this index does not give any information about the relationship between temperature and life. Thus the material with higher TI is considered better independently of the slope of the thermal graph. This is true if the material

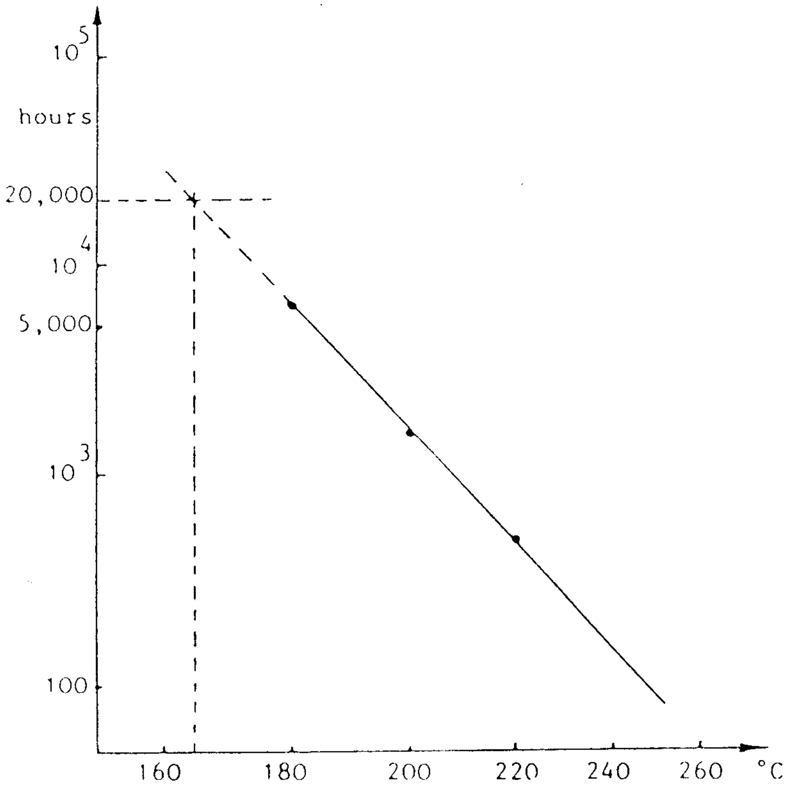


Figure 4.3: Example of thermal graph.

is exposed to the constant temperature of the *TI*. Since in service temperature is not constant, usually being lower but sometimes higher than the *TI*. Therefore, the slope of the line is very important in order to assess the thermal behavior of materials.

Another quantity is proposed for this purpose, the “Thermal Endurance Profile” (*TEP*) which consists of three numbers: the *TI*, the temperature corresponding to a time to reach the end point of 5,000 hours and the temperature corresponding to the lower unilateral 95 % confidence limit on the temperature at 5,000 hours. The *TEP* permits the thermal behavior of materials to be predicted, because the thermal life-line is plotted on a special paper where the line is normally straight. Therefore, the two points at 20,000 and 5,000 hours can make determination of the slope of the line and evaluation of endurance.

The recent IEC proposals have emphasized this point by introducing the “Halving Interval” (*HIK*), in Kelvin degrees, the temperature interval, in terms of $1/T$, corresponding to halving life. By substituting in equation (4.12) for two lives L_1 and $L_2 = 2\,L_1$, and dividing the equations, the result is:

$$2 = \exp\left[B\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right] = \exp\left[B\ \left(cT_1 - cT_2\right)\right] \qquad (4.15)$$

The following relationship is derived:

$$HIK = \frac{1}{T_2} - \frac{1}{T_1} = cT_1 - cT_2 = \log n\, 2/B = 0.693/B \qquad (4.16)$$

The halving interval is a measure of the slope of the thermal graph, which permits the influence of the temperature changes on the remaining life of electrical insulation to be estimated.

Note that the halving interval HIK and coefficient B are inversely proportional. This means that the higher the halving interval the worse the thermal behavior of materials.

The halving interval is now proposed by the IEC for evaluation of the slope of the thermal life graph, although the same could be performed by the TEP.

On the other hand, the TEP is not disregarded, as it contains additional information on the uncertainty of the results obtained; yet, the difficulty of obtaining this information suggests using the HIK instead of the TEP.

The actual degree of material degradation is revealed, although the intimate relationships between these properties and the aging reactions are unknown.

4.6.1.4 ANALYTICAL TEST METHODS

The analytical test methods are used for the determination of the activation energy of the degradation reaction. The general principle of the analytical procedures is to estimate the slope of the thermal endurance line by reaction rate constant measurements. The simplest mathematical approach to the rate theory shows that under the assumption of a predominant chemical reaction in the temperature range of test and extrapolation, the reaction rate can be written as [79,85-87]:

$$dc/dt = -K(T) \quad c^n \qquad (4.17)$$

Where,

c is the concentration of a chemical constituent of the insulation which is changed by thermal aging.

$K(T)$ is the reaction rate constant.

n is the reaction order.

The expression for $K(T)$ can be derived by the Arrhenius model:

$$K(T) = K_T \quad \exp\left(-E/kT\right) \qquad (4.18)$$

Where,

K_T is the pre-exponential term.

E is the apparent activation energy.

k is the Boltzmann constant.

Or by the Eyring model [88]:

$$K(T) = \left(kT/h \right) \exp\left(- \Delta G / kT \right) \tag{4.19}$$

Where,

h is Planck’s constant.

ΔG is the free energy corresponding to the height of the energy barrier to be overcome for the development of degradation reactions.

Once selecting a limit value c_L for concentration, the same as property end-point selection, the following is derived from equation (4.17):

$$- \int_{c_o}^{c_L} dc / c^n = \int_0^{t_L} K(T) \; dt \tag{4.20}$$

Where t_L is the failure time and c_o is the initial reactant concentration. By substituting Arrhenius model in equation (4.20) and integration:

$$F(c_L) \;=\; K_T \quad \exp\left(-{}^{B}\!/_{T}\right) \; t_L \tag{4.21}$$

Where,

$F(c_L)$ is a function representing the integral of the left hand side of equation (4.20).

B = E/k.

By logarithms, equation (4.21) becomes:

$$\log t_L \;=\; \log\left[{}^{F(c_L)}\!/_{K_T}\right] \;+\; {}^{b}\!/_{T} \tag{4.22}$$

Equation (4.22) provides straight thermal endurance line in the log t_L against ($1/T$) plot. The slope of the line in equation (4.22) is $b = B/2.3$ [85].

The selected analytical method should lead to determination of the activation energy of a reaction that can be dominant for the degradation of the insulating material, with reference to service stresses.

Extrapolations from high temperatures can give unrealistic results, as shown elsewhere [82]. The rate theory, which describes the thermal aging of many polymers very well, has been reported in several papers [61-62,82].

According to this theory, thermal life is given by [82]

$$t = \frac{h}{kT} \exp\left[\frac{\Delta G}{kT}\right] \tag{4.23}$$

where h is the Planck constant and ΔG, is the activation free energy and is given by:

$$\Delta G = \Delta H - T\Delta S \tag{4.24}$$

where ΔH and ΔS are the activation enthalpy and entropy, respectively.

Not only equation (4.23) does not contain any adjustable constant but it also depends on ΔS whereas the Arrhenius equation does not take it explicitly into account. Therefore, thermal aging results should be plotted on a log (tT) *vs.* $1/T$ graph, not on a log t *vs.* $1/T$ graph to yield reliable predictions.

4.6.2 VOLTAGE AGING

There exists a need for voltage endurance testing of insulating materials and systems. Two approaches are available at this time in voltage endurance testing. One attempts to increase the amplitude of the stress at constant frequency, while the other tries to maintain constant amplitude but increases the frequency. The first approach is limited by the breakdown strength of the material and does not allow much room for acceleration. The other one offers obviously much more flexibility in terms of frequencies but one has to be aware of the dependence of the materials' electrical properties on frequency. When the dielectric loss increases with frequency significantly, the temperature rise resulting there would add its own aging effect. Watson [90] indicates that the number and magnitude of discharge pulses may not remain constant as the frequency of the applied voltage increases.

It has been noted that electric stress, in the absence of internal discharges, can cause changes in material properties. Some ascribe the changes to electrochemical reactions, while others express the suspicion that the observed changes are really caused by partial discharges but the corona detecting system is too insensitive [91].

4.6.3 MECHANICAL AGING

As the sizes of turbine generators and transformers increase so do the mechanical forces that can stress the integrity of their insulation systems. These forces consist of: (a) electromagnetic vibration at twice the power frequency, inducing fatigue, (b) differential expansion forces due to the temperature variations following load changes, and (c) impact forces due to electrical faults.

4.6.4 COMBINED ENVIRONMENT AGING

Most electrical equipment is subjected to multiple stresses, and there is no electrical component or electrical device that operates without electrical stress and concomitant temperature caused by electrical losses in the dielectric and/or in the conductor. A large segment of equipment in the machinery area subjects its insulation to mechanical stresses.

Fort and Pietsch [92] demonstrated that consecutive thermal and voltage tests do not provide the same aging as obtained when both are applied simultaneously. The results obtained from a sequential exposure of materials to thermal aging and radiation stresses can be misleading. Insufficient data are available to permit calculations of degradation rates needed to predict service life when more than one stress is acting simultaneously on the material. Exploratory work by Campbell [93] has demonstrated that the life of insulating materials in environments combining radiation with high temperatures is far different from that obtained in the individual environments or from sequential exposures to each environment. Each material is affected differently, with some showing an accelerated degradation while others have a longer life in some environmental combinations.

The possible aging mechanisms of cable insulations are illustrated in Table VII [94].

4.7 PVC AND XLPE INSULATIONS

Polyvinylchloride (PVC) and polyethylene (PE) are the principal materials used in the wire and cable industry. They provide insulation and jacketing for more than 30,000 different types of wire and cable products [14]. In Canada, for example, PVC makes up 60% of the market; polyethylene 34% and numerous other resins comprise the remaining, 6% [95]. In U.S., however, polyethylene and its copolymers is the primary resin, followed by PVC, nylons, fluoropolymers and others. Table VIII presents data for the 2000 volume of thermoplastic resins used in wire and cable [96].

The different types of polyethylene used in this industry are linear low-density (LLDPE), medium-density (MDPE), high-density, (HDPE), and cross-linkable polyethylene, (XLPE). Lesser amounts of nylon, polypropylene, styrenics, acrylic, thermoplastic elastomers; such as EPDM, fluoropolymers, and other resins are also used.

TABLE VII: POSSIBLE AGING MECHANISMS of CABLE INSULATION.

Aging factor	Aging mechanisms	Effects
Thermal		
- High temperature - Temperature cycling	- Chemical reaction - Incompatibility of materials - Thermal expansion - Diffusion - Anneal locked-in mechanical stresses - Melting / flow of insulation	- Hardening, softening, loss of mechanical strength, embrittlement - Increase tan delta - Shrinkage, loss of adhesion, separation, delamination at interfaces - Swelling - Loss of liquids, gases - Conductor penetration - Rotation of cable - Formation of soft spots, wrinkles - Increase migration of components
Low temperature	- Cracking - Thermal contraction	- Shrinkage, loss of adhesion, separation, delamination at interfaces - Loss / ingress of liquids, gases - Movement of joints, terminations
Electrical		
Voltage, ac, dc, impulse	- Partial discharge (PD) - Electrical treeing (ET) - Water treeing (WT) - Dielectric losses and capacitance - Charge injection - Intrinsic breakdown	- Erosion of insulation →ET - PD - Increased losses and ET - Increased temperature, thermal aging, thermal runaway - Immediate failure
Current	- Overheating	- Increased temperature, thermal aging, thermal runaway
Mechanical		
Tensile, compressive, shear stresses, fatigue, cyclic bending, vibration	- Yielding of materials - Cracking - Rupture	- Mechanical rupture - Loss of adhesion, separation, delamination at interfaces - Loss / ingress of liquids, gases
Environmental		
Water / humidity Liquids / gases Contamination	- Dielectric losses and capacitance - Electrical tracking - Water treeing - Corrosion	- Increased temperature, thermal aging, thermal runaway - Increased losses and ET - Flashover
Radiation	- Increase chemical reaction rate	- Hardening, softening, loss of mechanical strength, embrittlement

TABLE VIII: VOLUME of US THERMOPLASTIC RESINS in WIRE and CABLE – 2000.

Thermoplastic resin	**Million lb.**	**Percent**
Polyethylene and copolymers	578	46%
PVC	486	39%
Nylons	74	6%
Fluoropolymers	50	4%
Polypropylene	16	1%
Other	53	4%
Total	**1257**	**100%**

All polymers, in a perfectly pure state, at room temperature, are completely non-toxic, since they are nearly inert and insoluble. They all undergo degradation and decomposition when exposed to heat during formulation or molding into products. They also tend to break down when subject to the mechanical stress of molding or extrusion. All products made from polymers are degraded by the light, heat, stress, and air pollution. For this reason, one or more stabilizers are required for each type of plastic.

4.7.1 POLYVINYLCHLORIDE (PVC)

Polyvinyl Chloride (PVC) is a polymer, or large chain-like molecule, made up of repeating units of Vinyl Chloride (a monomer). It is polymerized by several different methods from the basic vinyl chloride monomer. PVC begins with the manufacture of elemental chlorine gas by the energy intensive electrolysis of salt. The chlorine is then reacted with ethylene to produce ethylene dichloride (EDC). EDC is then converted into vinyl chloride monomer (VCM), which is then polymerized to form pure PVC plastic. The latter is then mixed with various additives to make PVC-compounds for wire and cable.

The PVC properties include good resistance to impact loads and fire resistance. PVC does not retain these properties well at low or elevated temperatures [97]. The different polymerization processes determine the particular properties of the respective polymer. Such modifications employ plasticizers to impart flexibility, stabilizers to prevent heat degradation, lubricants to facilitate processing, and fillers for a diversity of reasons, including cost reduction of the final compound, better electrical properties, and many general-purpose needs as, for example, pigments if a color is desired.

PVC has traditionally been the polymer cable construction due to its easy processing and good insulation performance. Even now with the trends toward using XLPE and other polymers, PVC still makes up approximately 50 % of the polymer volume used in cable construction [98]. Much of the PVC used for insulation purposes is colored to standard shades for ready identification. Colorants must be carefully chosen to maintain the insulation properties of the polymer.

PVC is widely used in wire and cable insulation, both as primary dielectric and as jacketing. It is introduced in 1932 and has become the standard insulation used on wire and cable rated at 1000 volts or less. Rigid PVC also finds some use in insulating parts. Molding compounds are available for various electrical components. In paste forms PVC can be applied as an insulation coating known as “plastisols”. PVC exhibits excellent chemical and moisture resistance. Its physical properties are good, temperature range is moderate from 65° C to 105° C, and has excellent electrical properties.

PVC compounds can be formulated to provide a broad range of properties from the standpoint of electrical, physical and chemical characteristics. However, in achieving superiority in one property, the other properties are usually compromised.

PVC has high dielectric strength and good insulation resistance. It is inherently tough and resistant to flame, moisture, and abrasion. Resistance to ozone, acids, alkalis, alcohols, and most solvents is also adequate. Compounding can impart resistance to oils and gasoline. Based on the specific formulation, temperature ratings range from 60° to 105° C.

PVC can be used in virtually all of the major types of wire and cable: low voltage building wire insulation and jacketing, low and medium voltage equipment cable jacketing, control cable jacketing, indoor telecommunications cable, automotive wire and flexible cords. It is an inherently flame and abrasion resistant material that is specially compounded for general-purpose applications at temperatures to 105 °C. It resists flames, oil, ozone, sunlight, and most solvents.

Wire and cable account for roughly 68% of PVC use in electrical products in 1999 [97]. PVC's greatest uses are in building wire, and its second greatest use is in electronics and telecommunications. PVC is used for cable inside buildings, due to its superior flexibility and flame retardant properties.

The principal technical characteristic that differentiates PVC and polyethylene (PE) wire and cable is the flame retardant qualities of PVC resin. Fire code specifications aim to ensure that insulation and jacketing materials are sufficiently flame resistant to delay the spread of fire long enough for people to safely evacuate a building. The presence of chlorine in the molecular structure of PVC resin, accompanied by synergists such as antimony trioxide, gives the material a much higher flame resistance than other thermoplastics such as PE. For this reason, PVC compounds are typically chosen as an inexpensive jacketing material in many interior wire and cable applications.

Disadvantages of PVC include a relatively high dielectric constant and dissipation factor. Plasticizer loss through evaporation or leeching eventually may cause embrittlement and cracking. PVC compounds significantly stiffen as temperatures decline, and are not generally recommended for uses which require flexing below – 10 °C. However, special formulations have been developed, which allow flexing to – 40 °C. [15]

4.7.1.1 COLORANTS

Colorants are added to wire and cable resins for identification purposes. Vinyl wire and cable compounds can be manufactured in virtually any color. There are two major types of colorants pigments and dyes. A pigment is insoluble and is dispersed as discrete particles throughout a resin to achieve a color. Pigments can be either organic or inorganic compounds. A dye is soluble in the resin and always an organic based material. Light stability is an important factor when selecting a colorant.

4.7.1.2 PVC COMPOUND

Compounding refers to mixing additives and fillers with PVC resin, in order to aid processing, improve functional performance, add aesthetic appeal, or decrease production costs. [14]

Three types of vinyl compounds are in general use - standard, semi-rigid and irradiated.

- **Standard PVC** is the 1000 volts or less plastic for hook-up, computer and control wires. Different compounds are used for 60°C, 80°C, 90°C and control wires. Different compounds are used for 60°C, 80°C, 90°C and 105°C service, and for commercial and military applications.
- **Semi-Rigid PVC** is much tougher than standard vinyl. It has greater resistance to abrasion and cut-through and more stable electrical properties.

- **Irradiated PVC** has improved resistance to abrasion, cut-through, soldering and solvents. Irradiation changes the vinyl from a thermoplastic to a thermosetting material.

Depending upon the formulation the rated temperature will vary from -55°C to 105°C, and dielectric constant values can vary from 2.7 to 6.5 [17]. A typical average PVC wire and cable compound consists about 50% resin, 20% plasticizer and 30% fillers and stabilizers. [14]

4.7.1.3 FLAME RETARDANCE

Thermoplastic or cross-linked PE resin with no flame retardant will burn easily in a fire. It is possible to load PE or XLPE with flame retardant additives to various degrees which will give the compound certain flame retardant properties comparable to that of PVC. Flame retardant PE or XLPE can be compounded to meet or exceed PVC in limiting oxygen index, but may have different performance or hazards than PVC in actual fire conditions. High levels of flame retardant additives may adversely affect some of the physical properties of the compound, such as melt index, tensile strength, elongation and flexural modulus. Where inadequate resistance to flame propagation is experienced, these compounds can only be used on larger diameter conductors having a higher heat sink.

An adverse consequence of the flame retardant nature of PVC is the risk of generating potential health and environmental effects associated with the combustion by-products generated when PVC is burned. The combustion by-products produced when PVC is burned include smoke, acid gases and organochlorine compounds. Low acid gas PVC compounds are available with the addition of brominated and antimony flame-retardants. These reduce the potential HCl concentration from levels of 20-36% down below 14% [14].

4.7.2 CROSS-LINKED POLYETHYLENE (XLPE)

Ethylene is a gaseous hydrocarbon made of two carbon atoms and four hydrogen atoms, C_2H_4, arranged as indicated in Figure 4.4-A. A strong bond for some hydrocarbons holds the two carbon atoms in the ethylene molecule together. However, under certain conditions, this bond will open as shown in Figure 4.4-B. This enables all the carbon atoms to be linked in which an ethylene molecule joins with others to form a chain. This chain, Figure 4.4-C, of ethylene molecules is called polyethylene (PE). PE chains are a three-dimensional shape, the hydrogen atoms being arranged along an inner zigzag chain of carbon atoms. PE chains can be short or enormously long and consist of many thousands of atoms.

PE is not built up of simple chains like the one presented in Figure 4.4. The

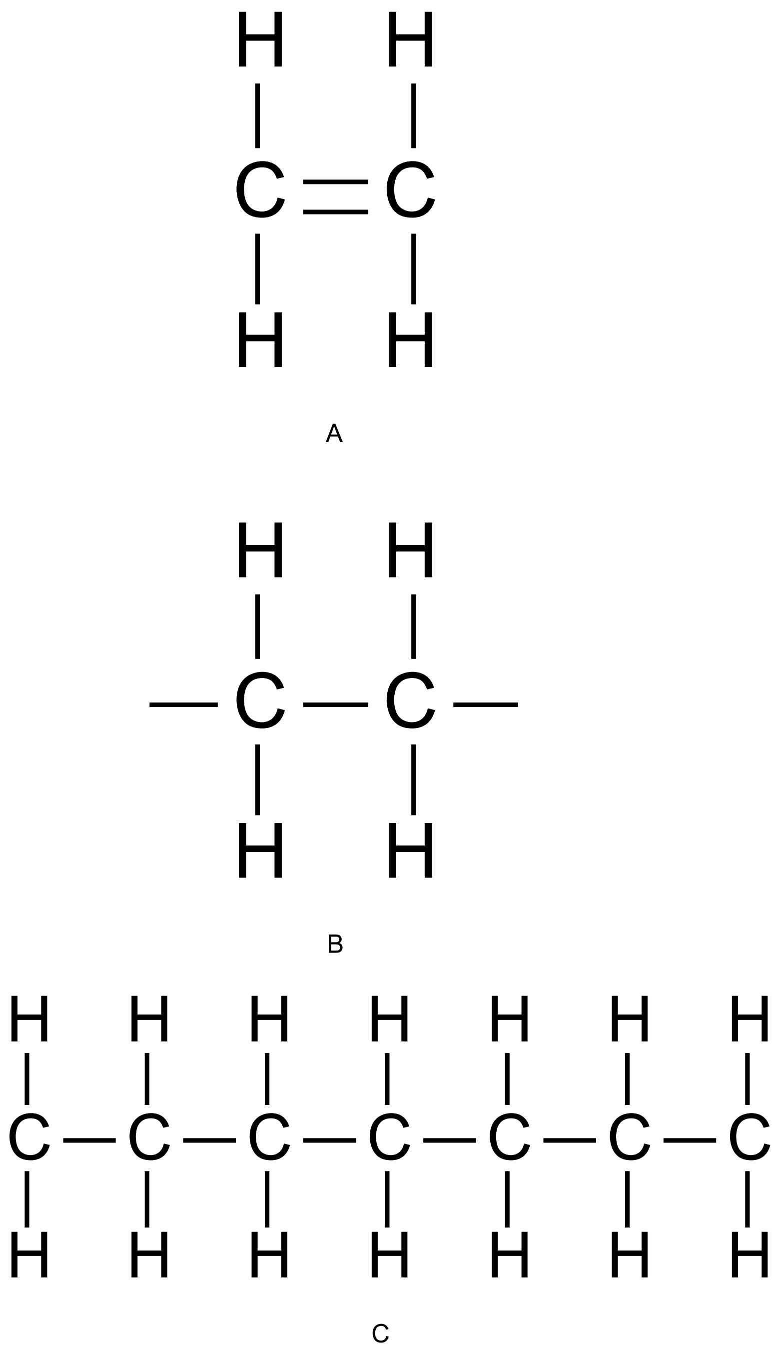


Figure 4.4: Structure of ethylene and its polymerized products as linear chain.

molecular structure of most low-density PE resins is far more complicated. The molecule is not a straight chain but one with a great number of short and long side branches like the branches of a tree point in all directions from various places along the trunk. Figure 4.5-A shows a schematic picture of such a side branching chain radiate three-dimensionally.

The presence of such side branches is the reason for variations of important physical properties such as density, hardness, flexibility and melt viscosity, that distinguish PE resins. Chain branches become points in the molecular network where oxidation may take place. It is not the only complication in the molecular structure; cross-linking, which is shown in Figure 4.5-B, but there are other factors. Such linking takes place between carbon atoms in neighboring chains. A network of cross-linked molecular chains may be compared to a number of heavily branched trees joined together somewhere along their branches.

Cross linked polyethylene (XLPE) or PE copolymer resins are useful for wire and cable coating. This type of resins may be compounded with a very high content of carbon black or other fillers. Controlled cross-linking results in a resin with excellent physical and heat resistant properties without impairing other essential properties. However, once the PE molecules are cross- linked, the polymer is changed from a thermoplastic to a thermoset and thus cannot be

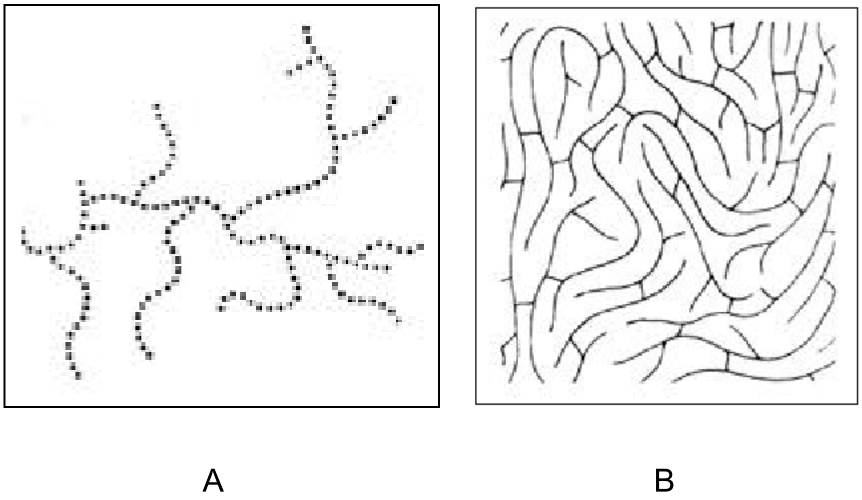


Figure 4.5: Polyethylene chain with side branches (A) and its simplified model of cross-linked (B).

softened and reused. PE can be cross-linked by irradiating the end product with electrons or gamma rays; or by adding peroxide and subjecting the mixture to heat and pressure. Both of these are free radical processes. An alternative method is to graft into the polymer chain a silane substituent, which will undergo a number of reactions, resulting in a crosslink when exposed to moisture.

4.7.2.1 ORDER AND DISORDER IN POLYETHYLENE

PE molecules are not all arranged parallel to each other. In some areas, the molecular chains are closely packed and lined up parallel in an orderly crystalline fashion. In other areas, the chains are randomly arranged liked boiled spaghetti. This structure is called amorphous. PE is always an amorphous mass above its melting point. A PE that remains totally amorphous at room temperature would be soft and greasy, thus useless for extrusion or molding applications. On the other hand, a totally crystalline PE would probably be too hard and brittle to be useful. The processor needs the right mixture of crystalline and amorphous regions to make good end products. The distribution of crystalline and amorphous areas is shown schematically in Figure 4.6. In general, low and medium density PE made by the high-pressure process has crystallinities ranging from 40 to 60%.

Density favorably influences a number of end product properties. One of these effects is the higher crystalline or the denser PE is the less permeable to

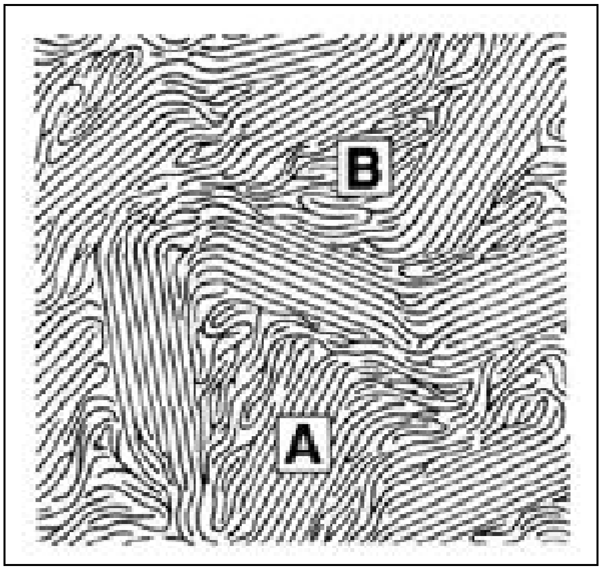


Figure 4.6: Crystalline (A) and Amorphous (B) regions in polyethylene.

gases and moisture; because there is small space between the more closely packed molecular chains. Gases and moisture penetrate more easily through the amorphous areas.

4.7.2.2 BASIC MOLECULAR PROPERTIES

Three basic molecular properties affect most of the mechanical and thermal properties essential for processing PE and obtaining good end products. These are: short chain branching, average molecular weight, and molecular weight distribution. Small variations in the molecular structure may improve or impair some of these properties considerably. The electrical properties of a PE resin are slightly affected by these three basic molecular factors. PE resins are available across a broad range of densities, between 0.88 g/cc to 0.96 g/cc. The ASTM generally uses a classification dividing PE resins into five ranges of density, shown in Table IX. The earliest PE resins had densities in the range 0.910 to 0.926 g/cc, e.g. LDPE. Recently, the very low-density PEs, those with a density less than 0.910 g/cc, were added to the family of PE resins [16].

4.7.2.3 EFFECTS OF AVERAGE MOLECULAR WEIGHT

The average molecular weight is inversely related to the melt index. In other words, as average molecular weight increases melt index decreases, and

TABLE IX: The 5 RANGES of POLYETHYLENE.

Density	**g/cm^3**	**ASTM D 1248**
Very Low	< 0.910	-
Low	0.910 – 0.925	Type I
Medium	0.926 – 0.940	Type II
High (Linear)	0.941 – 0.959	Type III
Very High	0.959 & >	Type IV

other words, as average molecular weight increases melt index decreases, and vice versa. The most suitable PEs for wire and cable applications should have a melt index in the range of 0.2-g/10 min to 3.0-g/10 min.

4.7.2.4 WIRE COATING

In addition to its electrical properties, tough, flexible, chemically inert PE make it an outstanding insulator for electrical wire and cable. Table X shows the different types of PE used in the wire and cable industry include low-density (LDPE), linear low-density (LLDPE), medium-density (MDPE), high-density (HDPE), chlorinated polyethylene (CPE) and cross-linkable polyethylene (XLPE) [27]. High-density resins have higher abrasion resistance and can better withstand mechanical abuse. They also exhibit greater tear resistance than low-density types, as well as higher tensile and shear strength.

High dielectric strength and very low electric conductivity make PE an excellent insulator for electric power cable at low voltage as well as high voltages. PE’s low dielectric constant allows for low capacitance and low electrical loss making it the choice for audio, radio frequency, and high voltage applications. PE is used in nearly all types of wire and cable products such as electronic, telephone and telegraph, power distribution, fiber optic, and building wire and cable products.

TABLE X: POLYETYLENE TYPES

Type	Notes
LDPE	Used in jacketing and insulation.
LLDPE	Has superior tensile strength and abrasion resistance.
MDPE	When blended with LDPE, imparts stiffness and abrasion resistance.
CPE	Contains 25% - 42% chlorine; used in jacketing due to toughness and flame retardancy.
XLPE	Cross-linked LDPE, usually with organic peroxides.

The power factor of PE that provides the measure of the power loss in the insulated conductor increases slightly with an increase in the temperature of the atmosphere or the electrical equipment. An increase in the humidity of the surroundings results in a slight increase in the power factor of PE.

PE and XLPE have better insulating properties than PVC and are used in more applications. The lower dielectric constant property allows less of the energy transmitted down the conductor to be lost through heat dissipation.

4.7.2.5 **CROSSLINKED WIRE INSULATION**

In the middle to late 1950s, cross-linkable PE compounds were introduced for coating power cable [16]. The unusual and excellent electrical properties of PE are extended to higher operating temperatures when used in cross-linkable materials. Cross-linked compounds are not thermoplastic and will not melt upon reheating. The process of cross-linking changes PE from a thermoplastic series of polymer chains into a single interwoven molecule, Figure 4.7. This cross-linking produces improved heat resistance, allows compounds to incorporate higher filler loadings, improves environmental stress crack resistance and gives higher tensile strength.

The most important advantage of XLPE over thermoplastic PE is the improved heat resistance. An XLPE insulated power cable can operate at

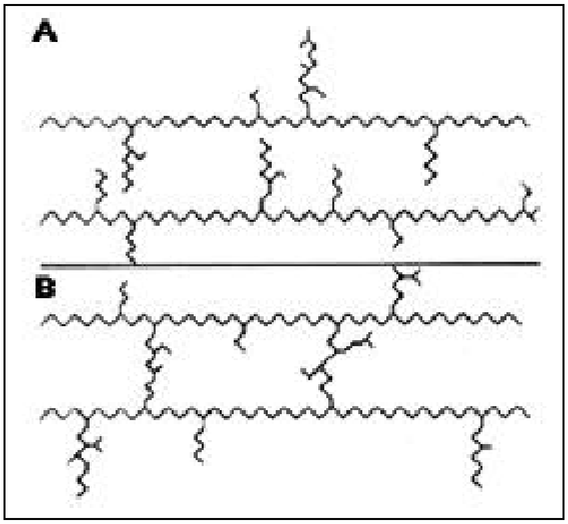


Figure 4.7: (A) Non-cross-linked LDPE. (B) Cross-linked LDPE.

conductor temperatures of 90°C, while the thermoplastic PE insulated cable operates at 75°C. Since conductor temperature is proportional to the amount of loading current through the cable, more power can be transmitted through an XLPE cable than through a non-cross-linked cable of the same size. Thus in heavily populated areas, fewer or smaller XLPE cables can be used. In appliance wire applications, cross-linking allows for 125°C service temperatures, well above the melting point of the non-cross-linked base resin.

The second most important improvement in XLPE is its capability to employ higher filler loadings without significant loss of physical properties. High filler loadings cause reduction in the physical properties of the polymer, particularly the tensile strength and elongation [16]. This enables the development of highly flame retardant, abrasion resistant or semi-conductive wire compounds while using relatively low cost polyethylene resins. One of the most successful commercial flame retardant wire and cable insulation compounds is based on a cross-linked ethylene-vinyl acetate (EVA) copolymer and contains greater than 50% by weight of flame retardant filler [16].

4.8 CHARACTERISTICS OF PVC AND XLPE INSULATED CABLE

4.8.1 TEMPERATURE RANGE

PVC can be compounded to retain its performance properties over a broad temperature range. Most PVC is rated for safe use at 90°C and 75°C in wet conditions, but some can be used safely up to 105°C. Most XLPE is rated for 90°C in both wet and dry conditions. Development work continues to increase the maximum temperature rating of both compounds to 105°C, in order to increase the capacity to carry current. Above about 107°C, XLPE softens somewhat, but is still more resistant to deformation than PVC, and continues to provide good insulation at temperatures up to about 150°C. [14]

4.8.2 FLEXIBILITY

The flexibility of compounded PVC is an important property in wire and cable applications. PVC, when properly compounded, can meet cold temperature performance standards as measured by cold bend and impact tests. Flexibility is required when installing cables through conduits and around bends in buildings. The use of PVC adds more flexibility to a cable than PE or XLPE does.

4.8.3 DURABILITY

The cross-linking of PE by catalytic action creates a much more durable thermoset material than the thermoplastic resins [14]. XLPE generally has higher tensile strength with higher resistance to abrasion and weathering. XLPE used mainly in insulation applications in power cables, but sometimes in jackets when resistance to abrasion or to hydrocarbon oils and fluids is required. Even in fire situations, flame retardant XLPE retains its physical structure far longer than flame retardant thermoplastic PE, making it the preferable alternative for higher risk areas.

XLPE is not usually as flexible compound as plasticized PVC. Some cables with an XLPE construction can be somewhat stiffer and more difficult to handle than ones having plasticized PVC in the construction.

4.8.4 PROCESSING

As thermoplastics, the processing of PVC wire and cable is a relatively straightforward extrusion process. In contrast, the processing of XLPE is a reactive system, which can require special handling of multiple raw material components, unique product curing technologies and increased process control requirements.

Peroxide-cure XLPE is a traditional process and the production rate is about one-third that of PVC, due to the slow curing process. The running rate of moisture-cure XLPE is about 75-90% that of PVC and operating costs are higher. Irradiation-cure XLPE has a minor share in the market, and is mostly for automotive use.

Table XI summarizes some of the technical factors between PVC and PE materials used in wire and cable constructions [14].

TABLE XI: TECHNICAL COMPARISON of PVC and PE in WIRE and CABLE.

Characteristic	**PVC**	**Thermoplastic PE**	**Cross-linked PE (XLPE)**	**TPEs**
Flame Retardance	High	Low (needs additives)	Low (need additives)	Low (need additives)
Acid Gas Emission	High	Low	Low	Low
Abrasion Resistance	High	Medium	High	High
Chemical Resistance	High	High	High	High
Tensile Strength	Medium	Medium	High	Medium
Weatherability	High	Medium	High	High
Dielectric (Energy Containment)	Medium	High	High	High
Heat Deformation Resistance	Medium	Low	High	High
Cold Impact Resistance	High (when compounded)	Medium	Medium	High
Cold Flex at – 40 ° C	High (when compounded)	Medium	Medium	High
Maximum Service Temp. (° C)	105	75	125-150	100-150
Ease of Processing	High	High	Moisture: Med. Peroxide: Low	High
Moisture Resistance	High	High	High	High
Moisture Permeation	High	Low	Low	Medium

CHAPTER # 5

EXPERIMENTAL PROCEDURE, RESULTS AND ANALYSIS

5.1 PRACTICAL PROCEDURES AND METHODOLOGY

5.1.1 INSULATING MATERIALS

Polyvinyl chloride (PVC) and cross-linked polyethylene (XLPE) insulation materials are the major insulating materials used in cable insulation industries. Different samples of these insulation materials are tested in this experiment.

Two main categories of each type are used in this study; namely, raw and manufactured insulated materials, Figure 5.1. For example, raw PVC is plastic that will be used in cable insulation industry, while manufactured PVC insulation specimens are collected from new cables. The raw XLPE material and manufactured XLPE insulation specimens are used in the experiment, too. Colorant effect on insulation material stability will be investigated by considering colored and non-colored samples as well.

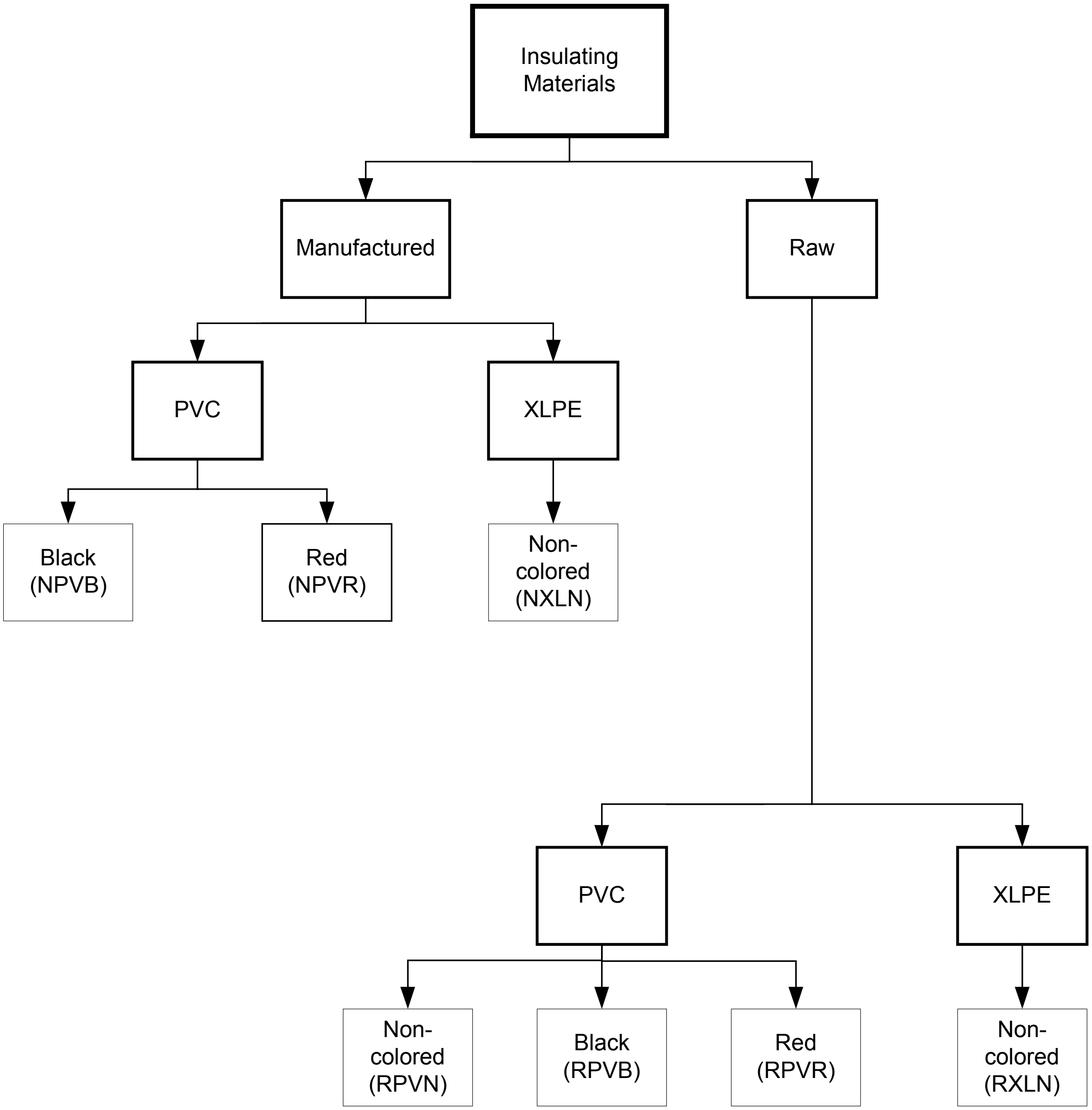


Figure 5.1: Sample set.

5.1.2 SAMPLING

A number of sample sets have been prepared for the experiment. Each set includes seven samples of PVC and XLPE insulation materials as illustrated and coded in Table XII.

The sample, which is shown in Figure 5.2, is prepared by filling a glass tube with specimens of insulating material. The weights of samples are recorded before and after thermal aging process in order to determine the weight loss due to aging. For safely handling, samples are placed inside a holder as shown in Figure 5.3.

5.1.3 THERMAL AGING PROCEDURE

The samples are arranged inside a glass container nearby its circumference to experience similar aging effect, Figure 5.4. This glass container is placed inside the thermal aging unit. This unit consists of a flexible heating tape, Brisk Heat from Briscoe Manufacturing Company, rounded on a glass container, which is placed in a well thermally isolated area, and connected to a digital pre-programmable controller as illustrated in Figure 5.5. The controller model is PARR 4842 from PARR Instrument Company equipped with J-type high temperature thermo-couple. The controller supplies power to the heater and

TABLE XII: INSULATING MATERIALS USED in the EXPERIMENT.

Sample #	**Insulating material**	**Code**
1	Raw* PVC non-color	RPVN
2	Raw* PVC black-color	RPVB
3	Raw* PVC red-color	RPVR
4	New cable** PVC red-color	NPVR
5	New cable** PVC black-color	NPVB
6	Raw* XLPE non-color	RXLN
7	New cable** XLPE non-color	NXLN

* Raw materials used in cable industry.

** Manufactured power cables insulation.

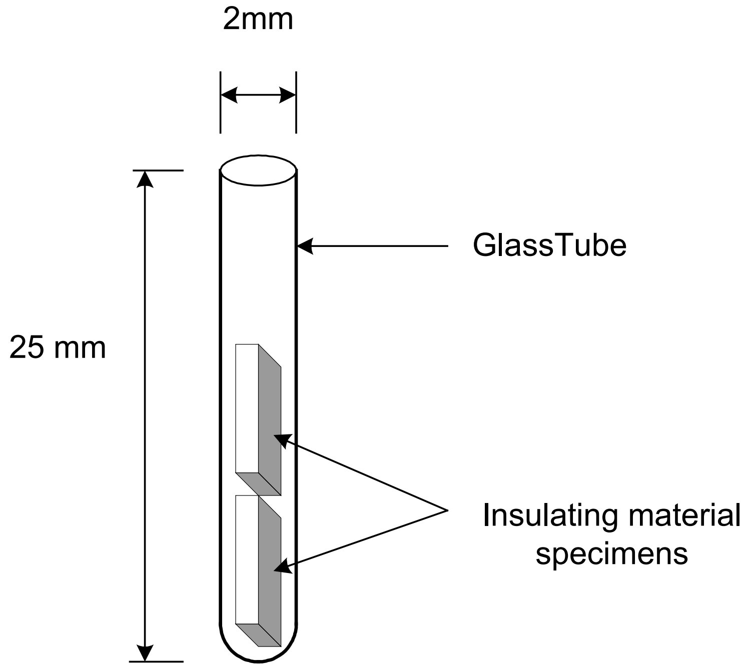


Figure 5.2: Sample preparation.

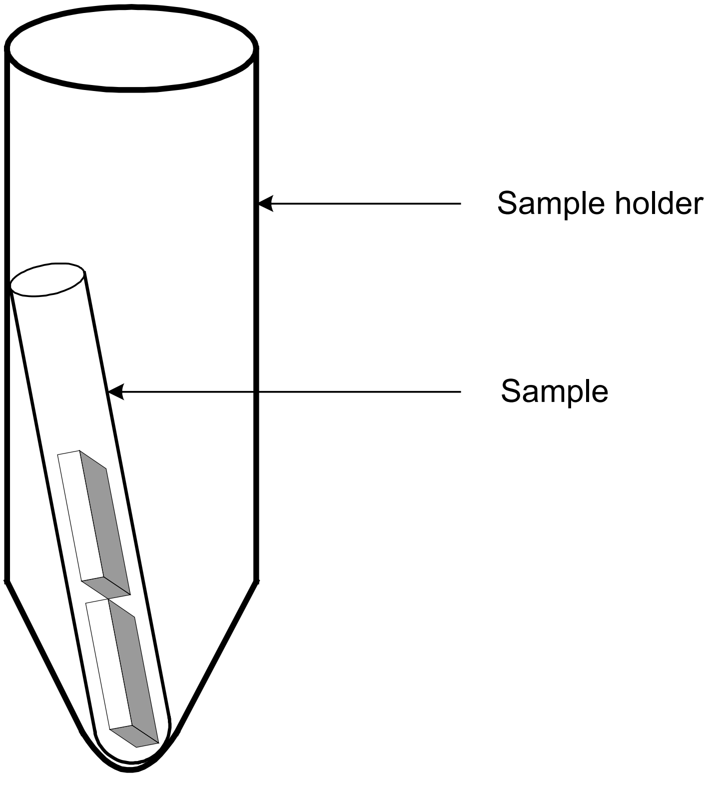


Figure 5.3: Sample inside holder.

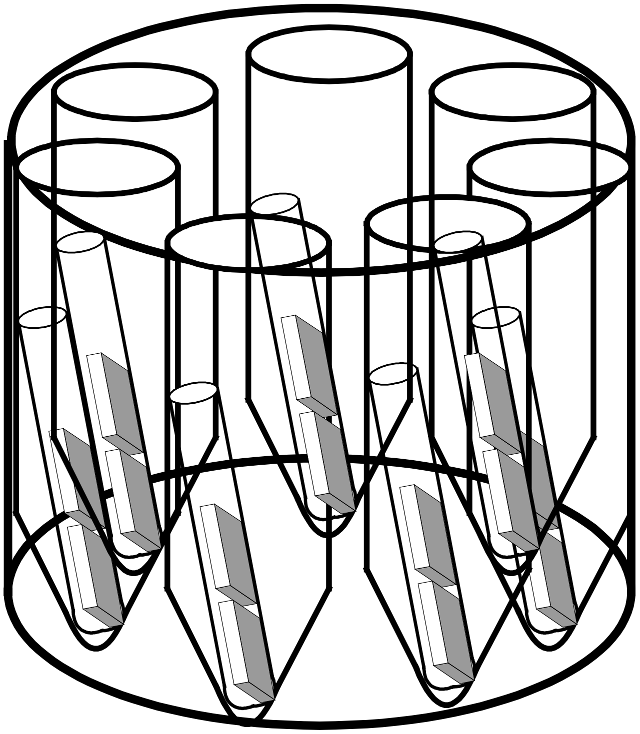


Figure 5.4: Samples arranged in a glass container.

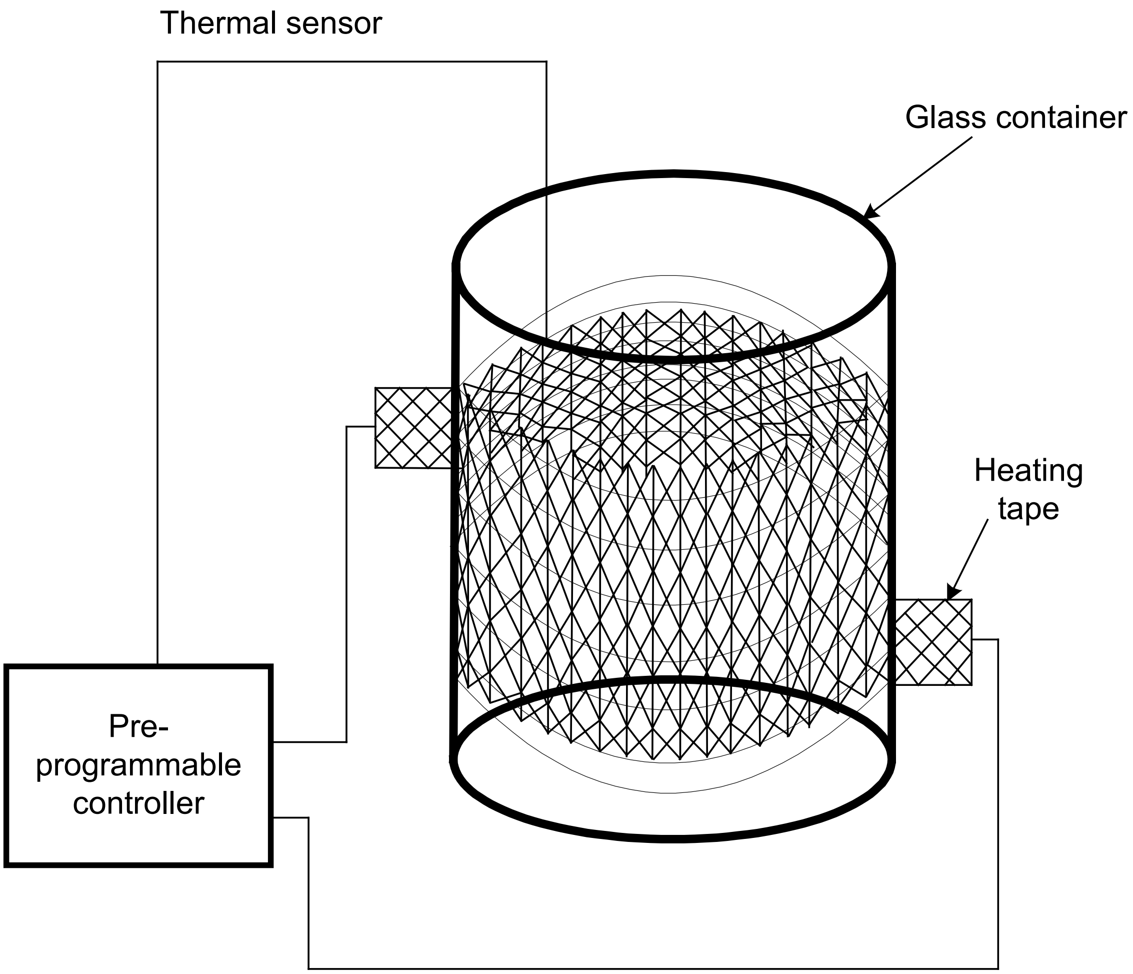


Figure 5.5: Heater tape rounded on a glass container.

control the temperature inside the glass container according to the pre-programmable condition. A thermal sensor of the controller is placed inside the sample holder in order to have a stable controlled environment for the aging process. In addition, an external digital thermometer manufactured by Omega Engineering, Inc. model 410B-T-F, is used as reference external values to confirm the thermal stability. The aging period depends on the aging temperature and type of insulation materials, and it varies between 400 hours and 2000 hours.

5.1.4 WEIGHT DIFFERENCE INVESTIGATION

Weight difference is a measurement of change in a physical property to achieve thermal endurance characterization of the tested materials. Digital balance from Mettler Instrument model AE200, with accuracy $\pm 1\times10^{-4}$ gram has been used to determine samples' weight before and after aging. All weights of samples were recorded at room temperature.

5.1.5 ESR SPECTROSCOPY

The ER series spectrometers are used to detect and measure the phenomenon known as electron paramagnetic resonance (EPR), that is called electron spin resonance (ESR), in a small sample of substance under test. The output of the instrument is in the from of a spectrograph covering a selected portion of the microwave region of the electromagnetic spectrum, which is displayed on a monitor and may also be plotted in ink on paper. Data acquiring unit also transfers it to different PC-file format that is handled by different ESR software as well as MS-Excel program. The spectrograph is used to analyze certain aspects of the chemical composition, molecular, and atomic structures of the substances being tested.

Electron paramagnetic spectroscopy is used in many areas of physics, chemistry, and increasingly nowadays, biology and medicine to provide information on the structure of molecules and atomic particles in paramagnetic substances whether in the gas, liquid or solid states.

These substances include transition elements, which are elements with unfilled inner electron shells, metals, various paramagnetic defect and impurity centers in crystals, and free radicals i.e., molecules or atoms possessing an odd number of electrons. The sensitivity of ESR techniques is particularly important for the study of very short-lived species that have to be created inside the detecting cavity.

The ESR spectrometer used is Varian, and the experimental parameters settings are shown in Table XIII. When weight test is carried out, parallel ESR spectroscopy test is performed too at room temperature.

TABLE XIII: EXPERIMENTAL PARAMETERS of ESR SPECTROMETER.

Experimental parameters	**Values**
Microwave bridge power	2 mW
Field controller module	
Field set	3330 gauss
Scan range	4.0 × 100 gauss
High frequency module	
Gain	1.25×10^4
Function	100 KHz
Time constant	1.0 sec
Oscilloscope Module	
Filter	Out
Field sweep	40
System Function Selector Module	
Oscilloscope Monitor	High frequency
Cavity modulation	High
Recorder input	High freq

5.2 EXPERIMENTAL RESULTS

5.2.1 CONVENTIONAL METHOD

The principle of the conventional method is to realize the aging tests on suitably selected samples at three or more constant temperatures [99]. The tested specimens are subjected to diagnostic procedures in order to detect the degree of aging. The significant properties that are influenced by thermal degradation reactions are measured. These properties are electrical, chemo-physical and mechanical properties. Since cables are mainly subjected in service to electrical, thermal and mechanical stresses, the properties selected for the conventional aging tests are electric strength, weight, tensile strength and modulus. Curves of property against time at different temperature are drawn and end-point criteria must be selected. End-point is the limit values of property variation beyond which the degree of deterioration is considered to reduce the insulation ability to withstand the actual service stresses. The thermal endurance lines of the tested materials can be plotted, one for each selected property end point.

The test temperatures are 130, 170 and 220 °C, and the property selected for the aging test performed is the weight. Figures 5.6 to 5.12 show the weight property against time curves for PVC and XLPE insulations. As can be seen, the weight property tested exhibits a sharp drop in the temperatures 170 and 220 °C.

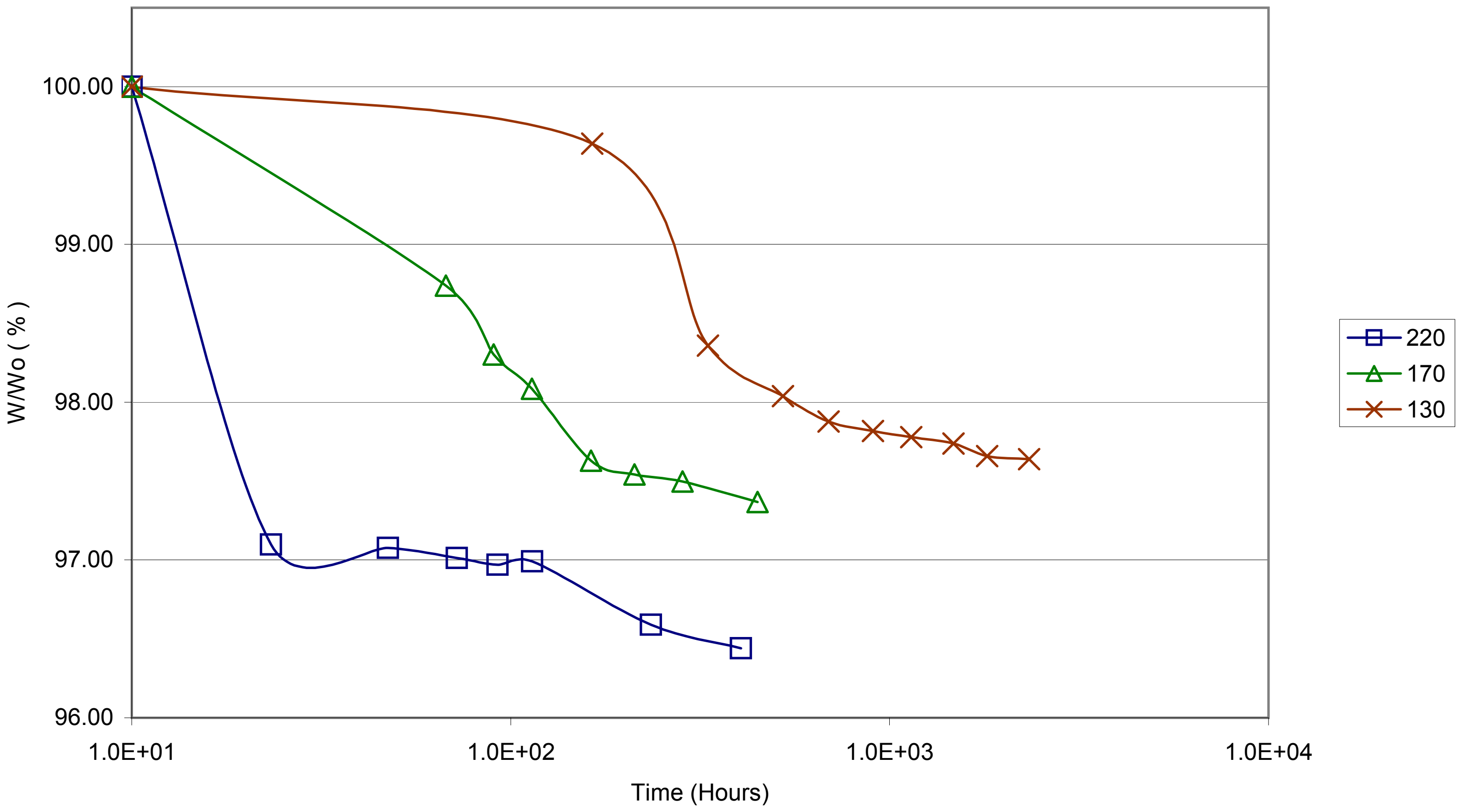


Figure 5.6: Weight versus aging time for RPVN.

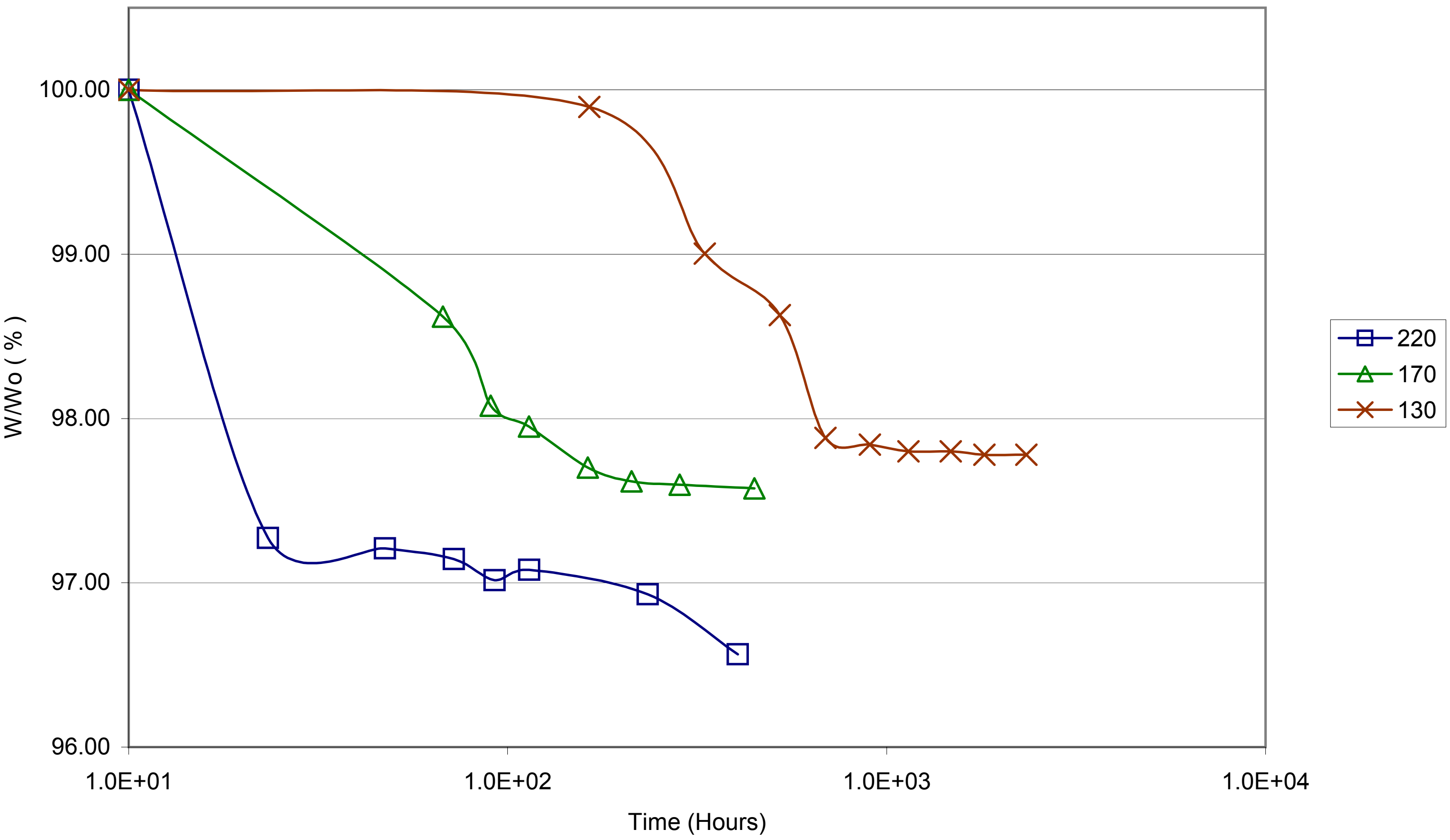


Figure 5.7: Weight versus aging time for RPVB.

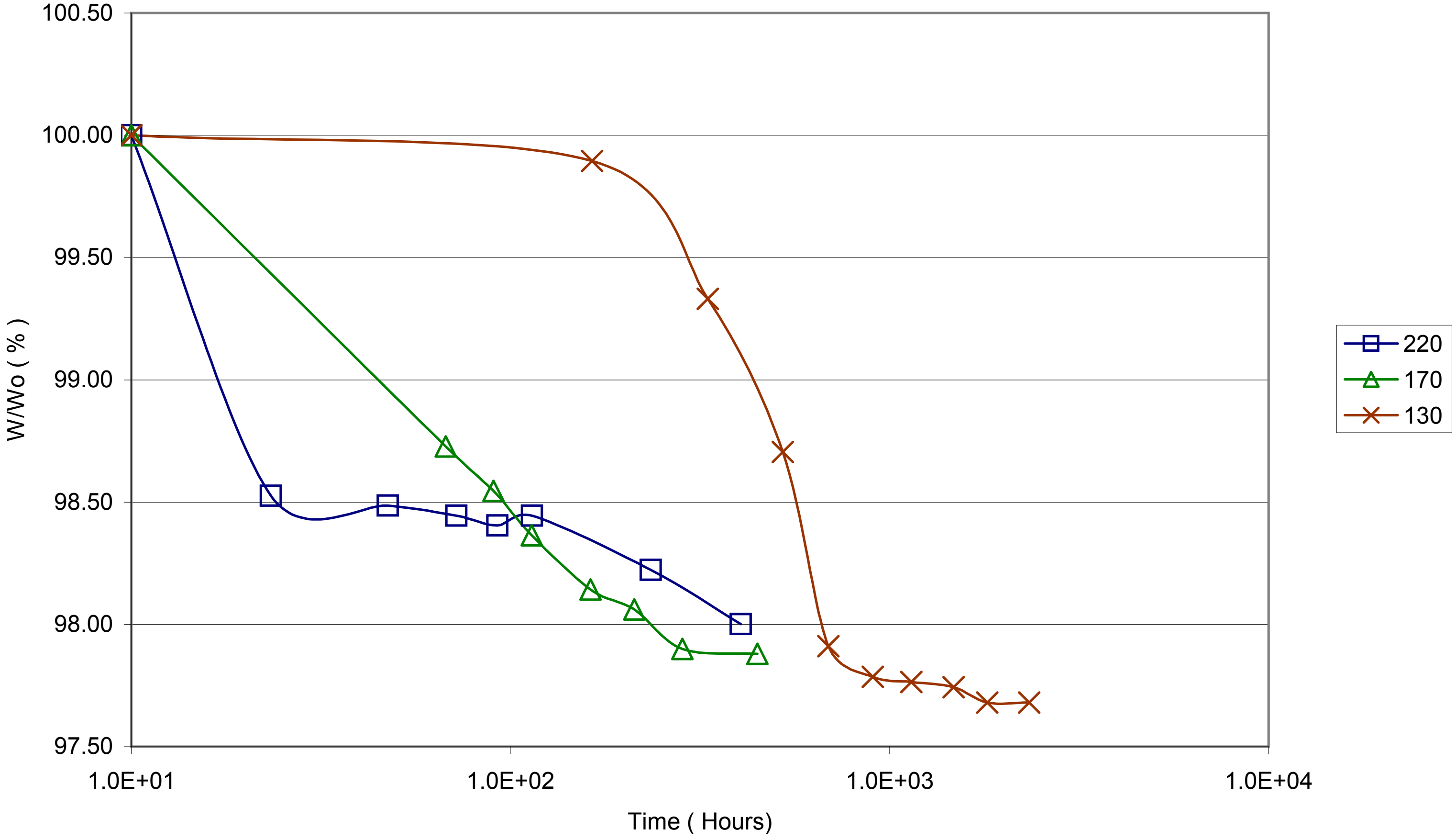


Figure 5.8: Weight versus aging time for RPVR.

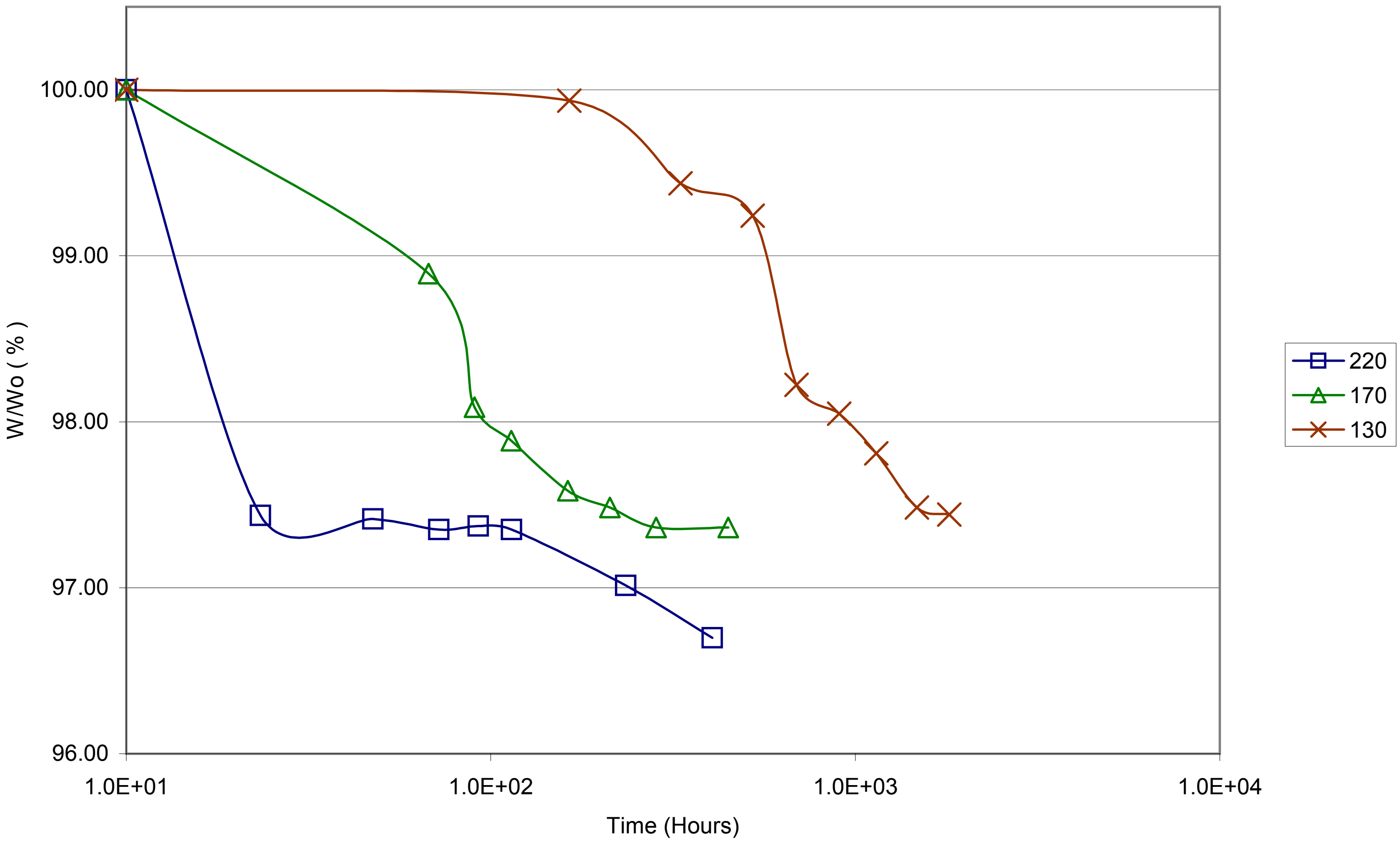


Figure 5.9: Weight versus aging time for NPVR.

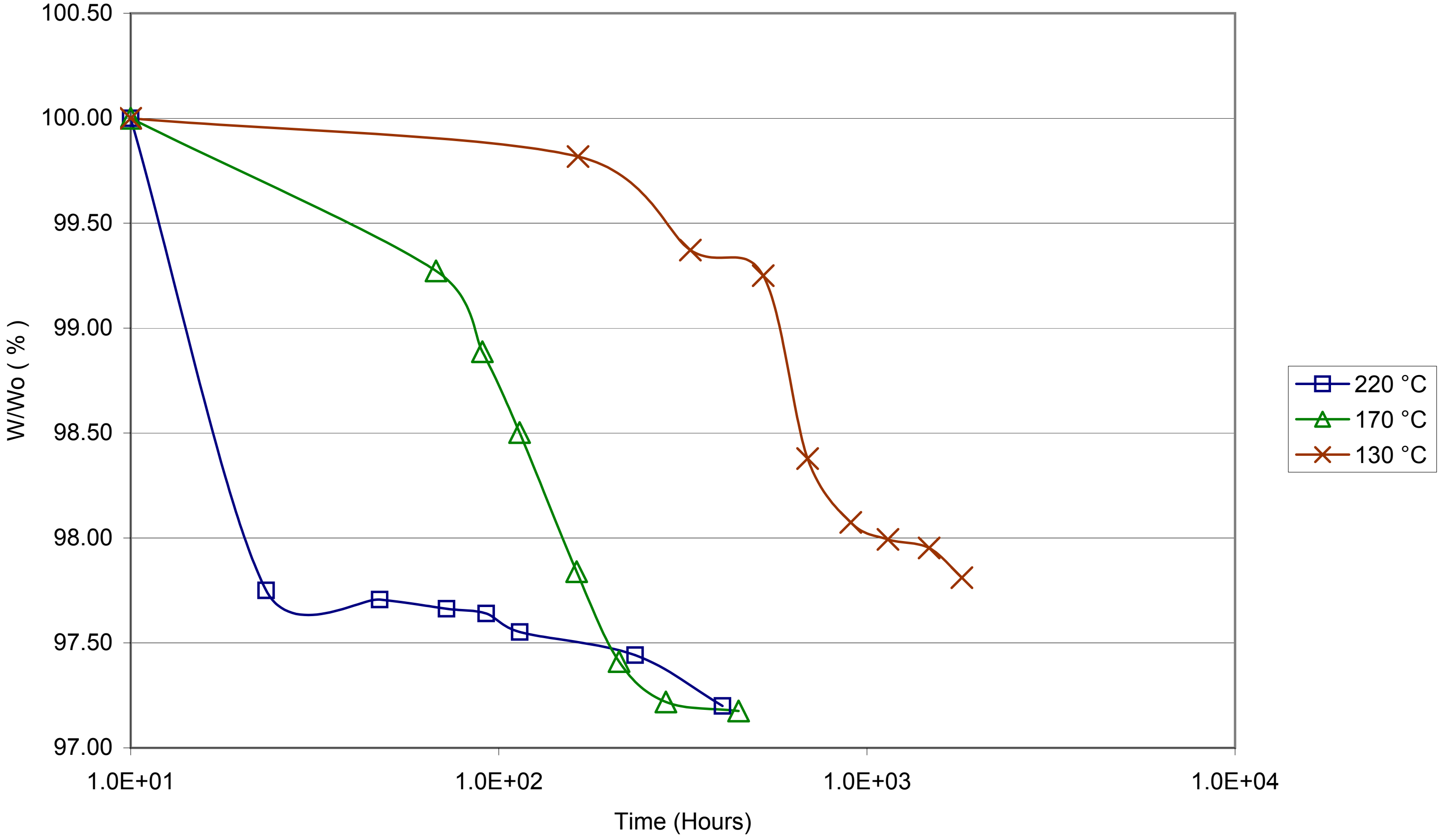


Figure 5.10: Weight versus aging time for NPVB.

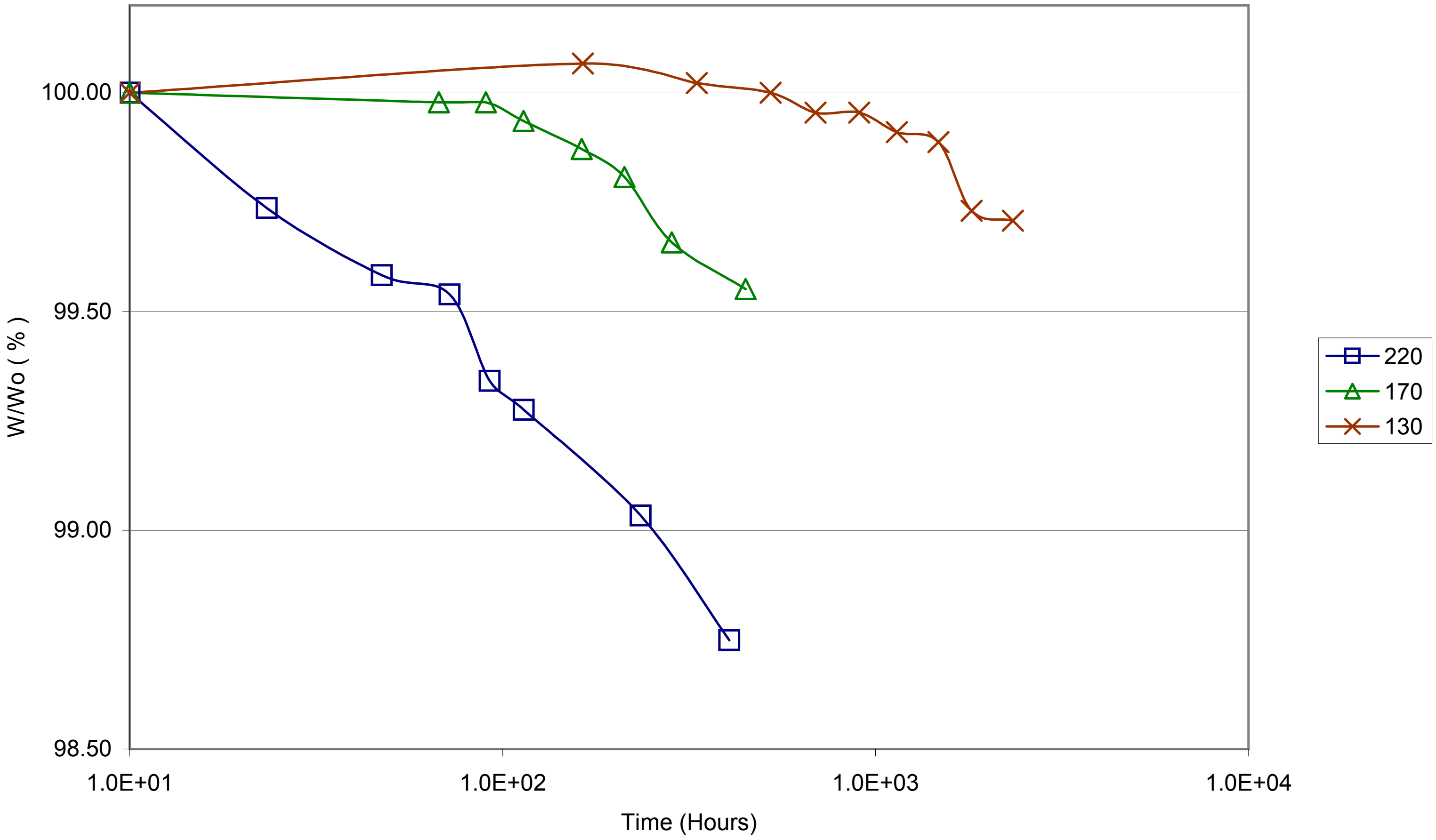


Figure 5.11: Weight versus aging time for RXLN.

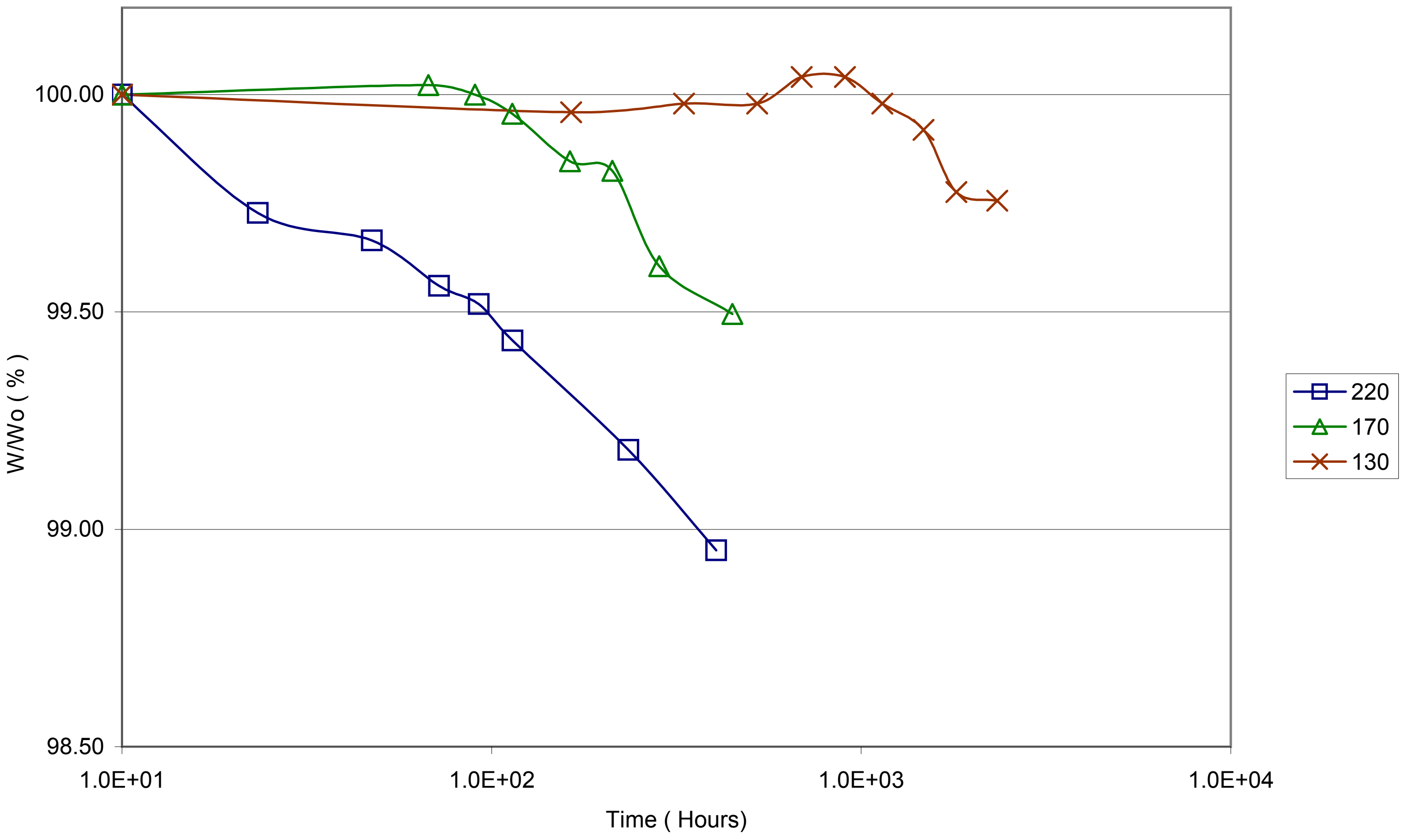


Figure 5.12: Weight versus aging time for NXLN.

On the contrary, at 130 °C the decrease is small and not monotonic for XLPE.

These results matches the results of conventional aging tests performed on XLPE insulation [78]. Figures 5.13. 5.14 and 5.15 show the property against time curves for electric strength, weight and tensile modulus, respectively [78].

Figure 5.16 shows the effect of colorants on the PVC insulation. It is clear that colorants enhance the thermal stability of PVC insulation, which must be carefully chosen to maintain the insulation properties.

Moreover, raw PVC insulation has better thermal resistance than manufactured PVC. This means that the manufacturing process has an effect on the thermal stability of the final product of PVC insulated cables as shown in Figure 5.17.

Weight loss test results of XLPE insulation indicate that raw XLPE has thermal stability not much better than manufactured XLPE as shown in Figure 5.18.

The comparison between the weight properties of PVC and XLPE is well observed in Figure 5.19. It clearly indicates that XLPE has thermal stability much better than PVC.

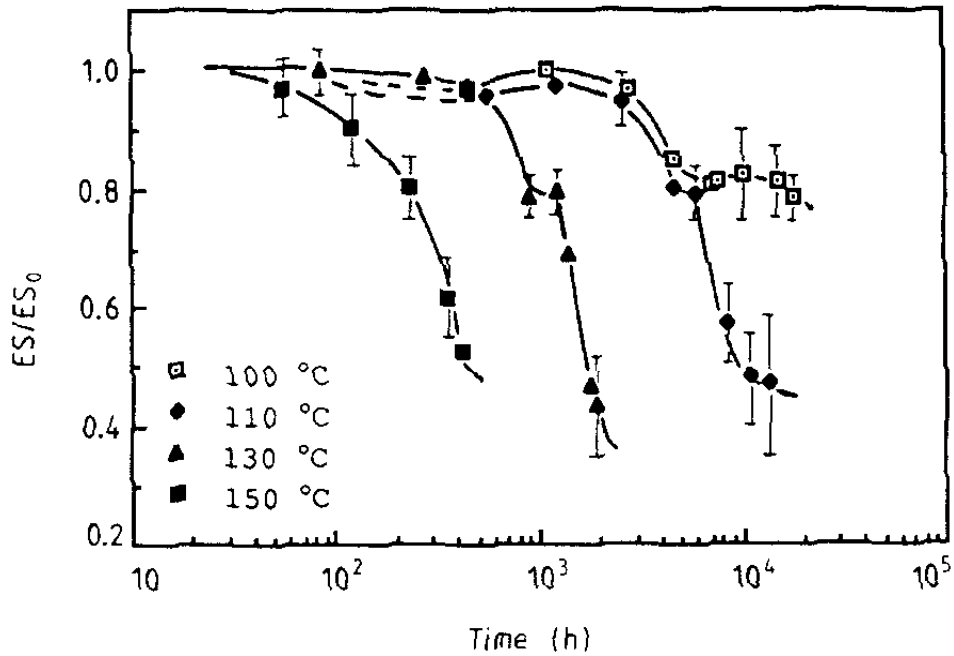


Figure 5.13: Electric strength against aging time.

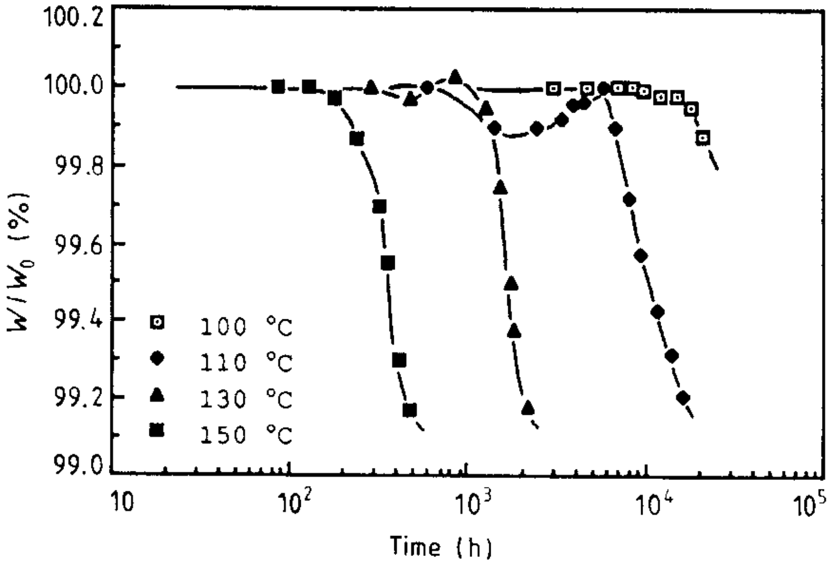


Figure 5.14: Weight against aging time.

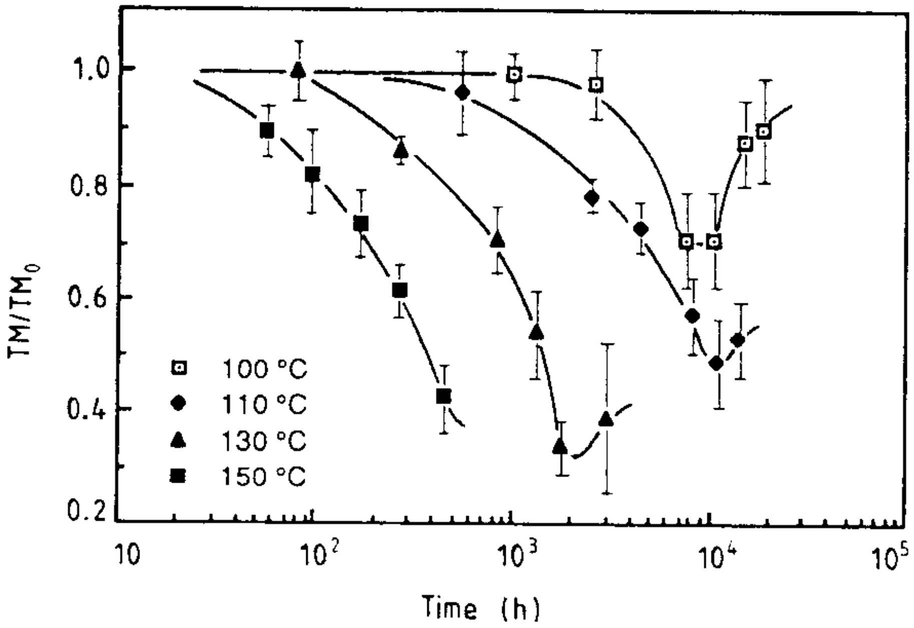


Figure 5.15: Tensile modulus against aging time.

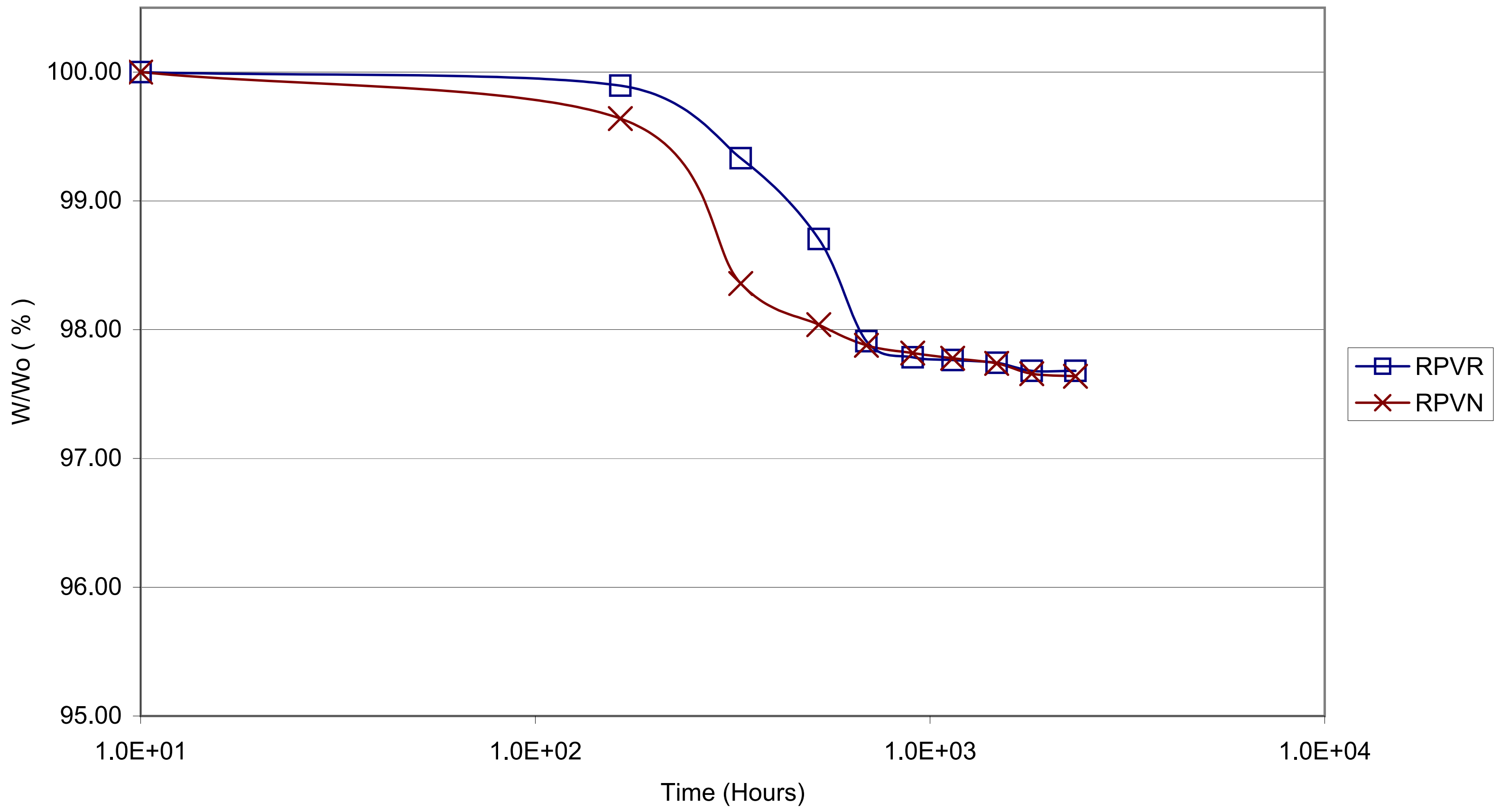


Figure 5.16: Weight property against aging time for colored and non-colored PVC insulations at 130 °C.

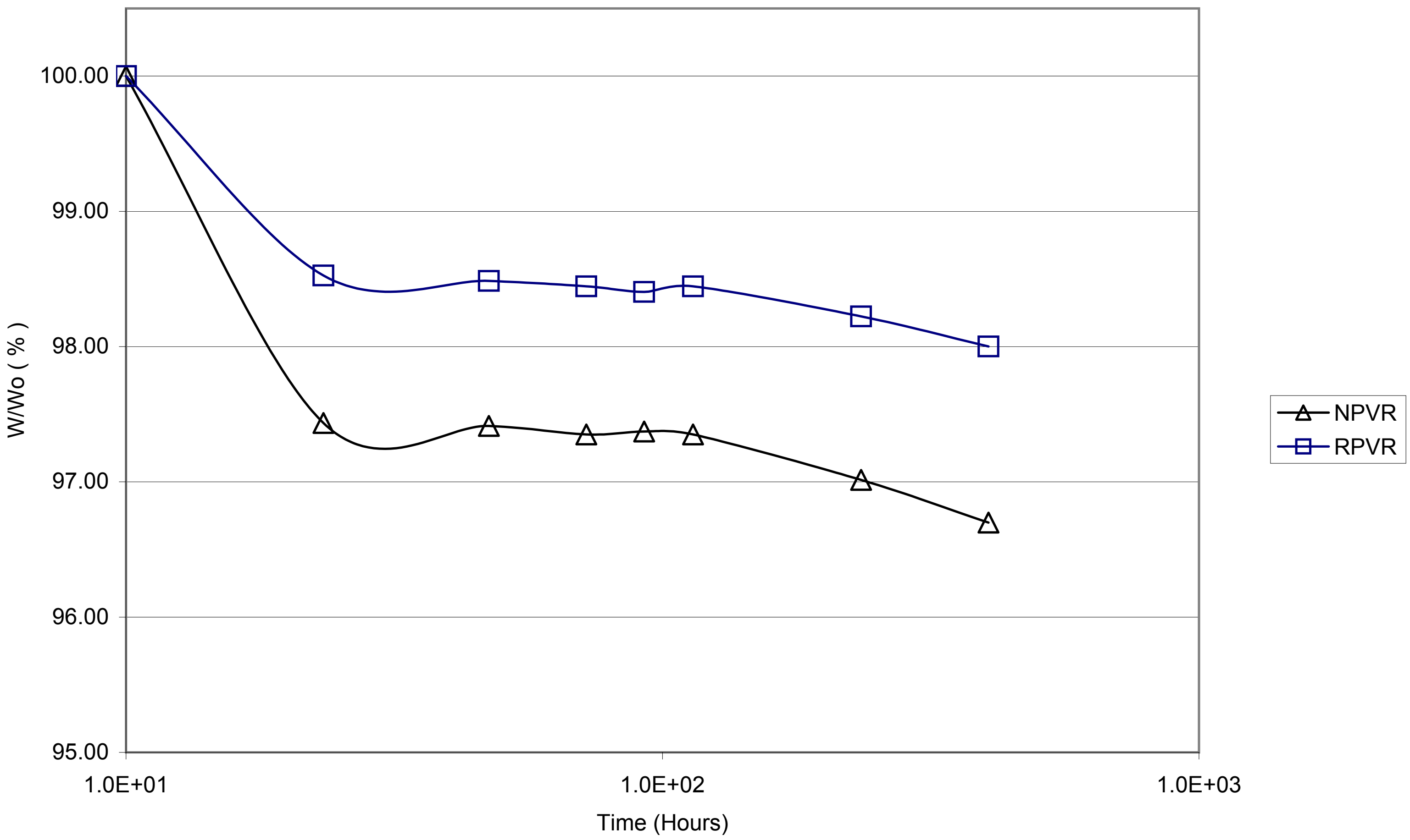


Figure 5.17: Weight property against aging time of raw and manufactured PVC insulations at 220 °C.

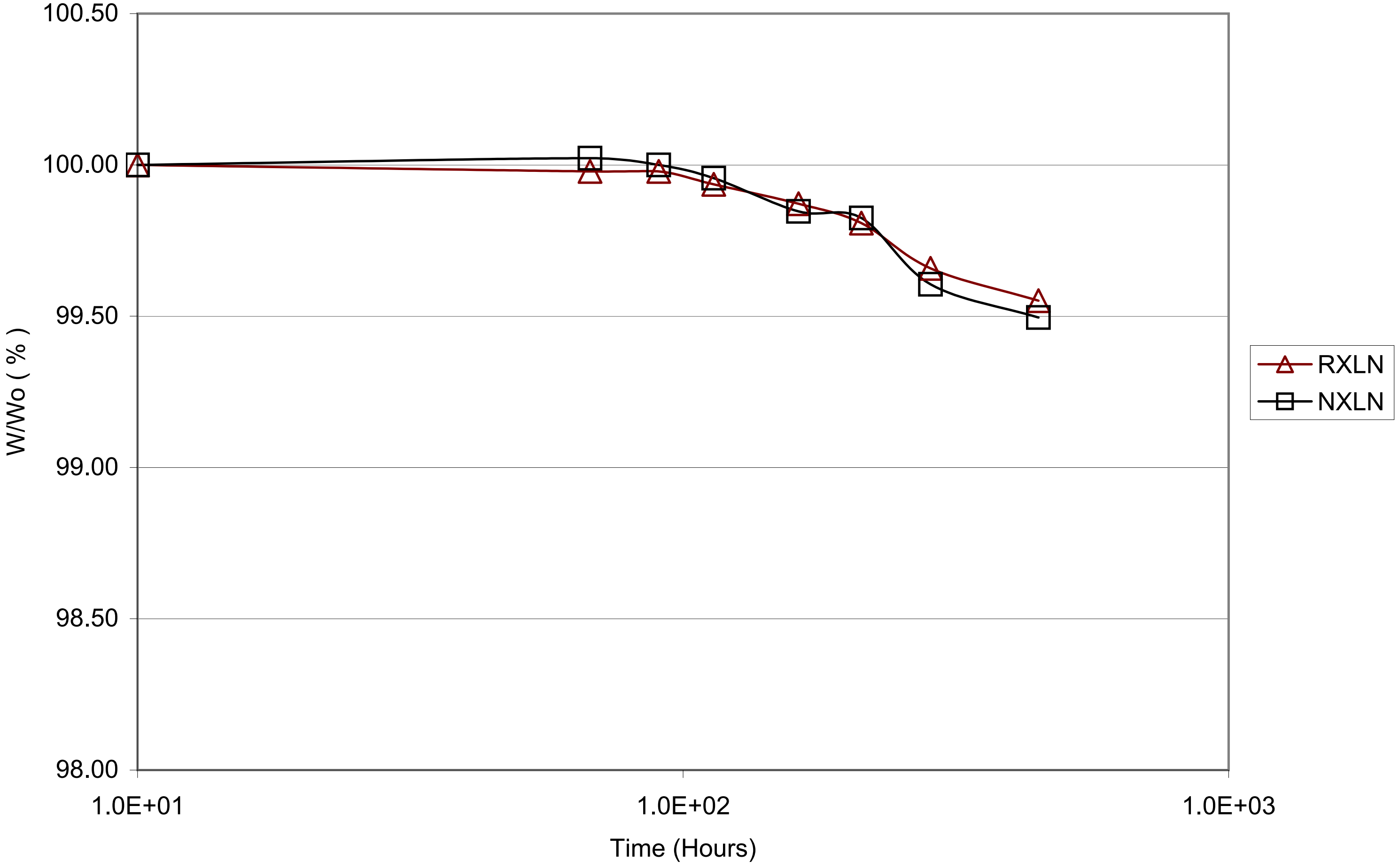


Figure 5.18: Weight property against aging time of raw and manufactured XLPE insulations at 170 °C.

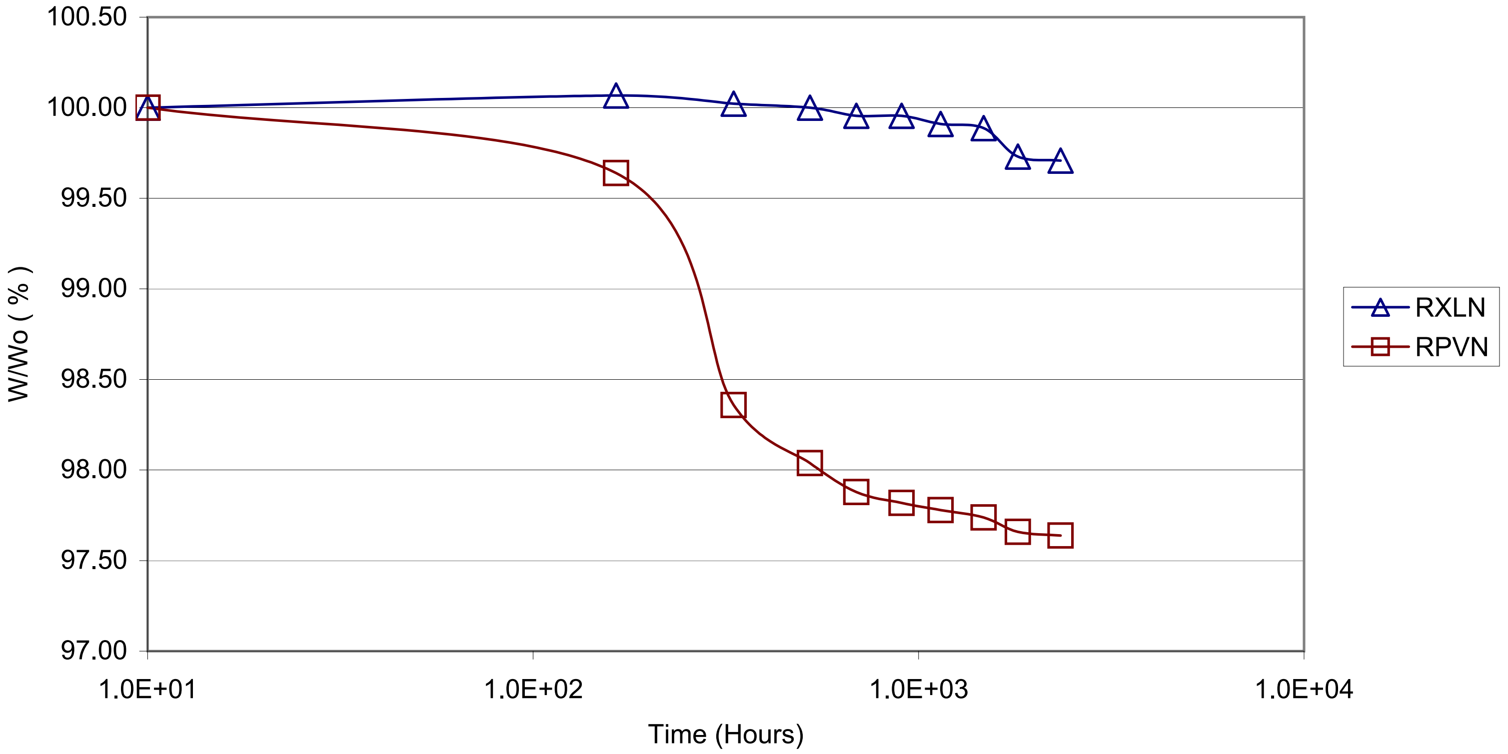


Figure 5.19: Weight of XLPE and PVC insulations versus aging time at 130 °C.

5.2.2 ANALTICAL TEST METHOD

The analytical test measure the evolution of the thermal degradation reactions to determine the slope of the thermal endurance line, b. The thermal endurance line can be plotted by assuming one point derived from a conventional aging test. This test is performed at a temperature higher than the minimum temperature pertinent to the conventional method. Fixing the endurance line at one point that results from a conventional test derives the ordinate intercept.

The thermal endurance characterization, on the basis of either conventional or analytical methods, then seems to provide a useful tool for insulation design with respect to the actual endurance to service stresses.

It is customary to perform laboratory temperatures in order to accelerate aging, and then extrapolate the results to operating conditions. Most extrapolations are done with Dakin's theory [54,55] based on the Arrhenius equation.

Electron spin resonance (ESR) test is one of the analytical methods that has special potential in material degradation analysis.

Several authors [84, 100-102] reported that γ-irradiated PVC in vacuum at room temperature gives a singlet-line spectrum of 25 G peak-to-peak width as shown in Figure 5.20. This spectrum was attributed to polyene radicals. This singlet-line ESR spectrum was also observed during thermal [103-109] and photo [110-113] degradation, and chemical dehydrochlorination [114] of PVC. A similar singlet-line spectrum has been obtained at room temperature during thermal degradation of PVC insulations as shown in Figures 5.21 and 5.22.

Two types of free radicals are formed during UV-irradiation of PVC; namely polyenyl and alkyl radicals, which decay at different rates. Alkyl radicals disappear at a much faster rate than polyenyl radicals, which exist even above 323 K. However, the results obtained at room temperature indicate the formation of the polyenyl radical during thermal degradation of PVC insulations.

Atchinson [115, 116], and Rabek and Ranby [110] investigated the decay of free radicals formed during irradiation of PVC. Figure 5.23 shows the decay curves of free radicals during warming of a UV-irradiated PVC sample. The concentration of free radicals formed during thermal aging of some PVC insulations are plotted in Figures 5.24 and 5.25.

Results in Figure 5.24 indicate that the onset of degradation of the non-colored PVC insulation is earlier than colored PVC insulation due to the existence of the colorant. According to cables manufacturers, colors pigments used in cable industry must be carefully selected to enhance polymer properties, which is confirmed with ESR results.

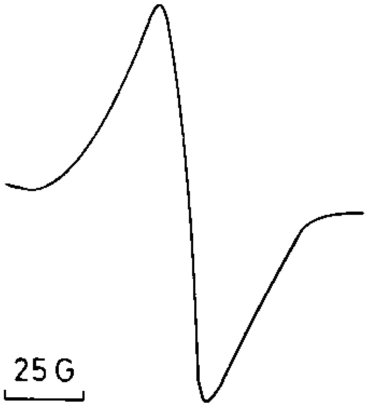


Figure 5.20: ESR spectra of PVC γ-irradiated at room temperature in vacuum.

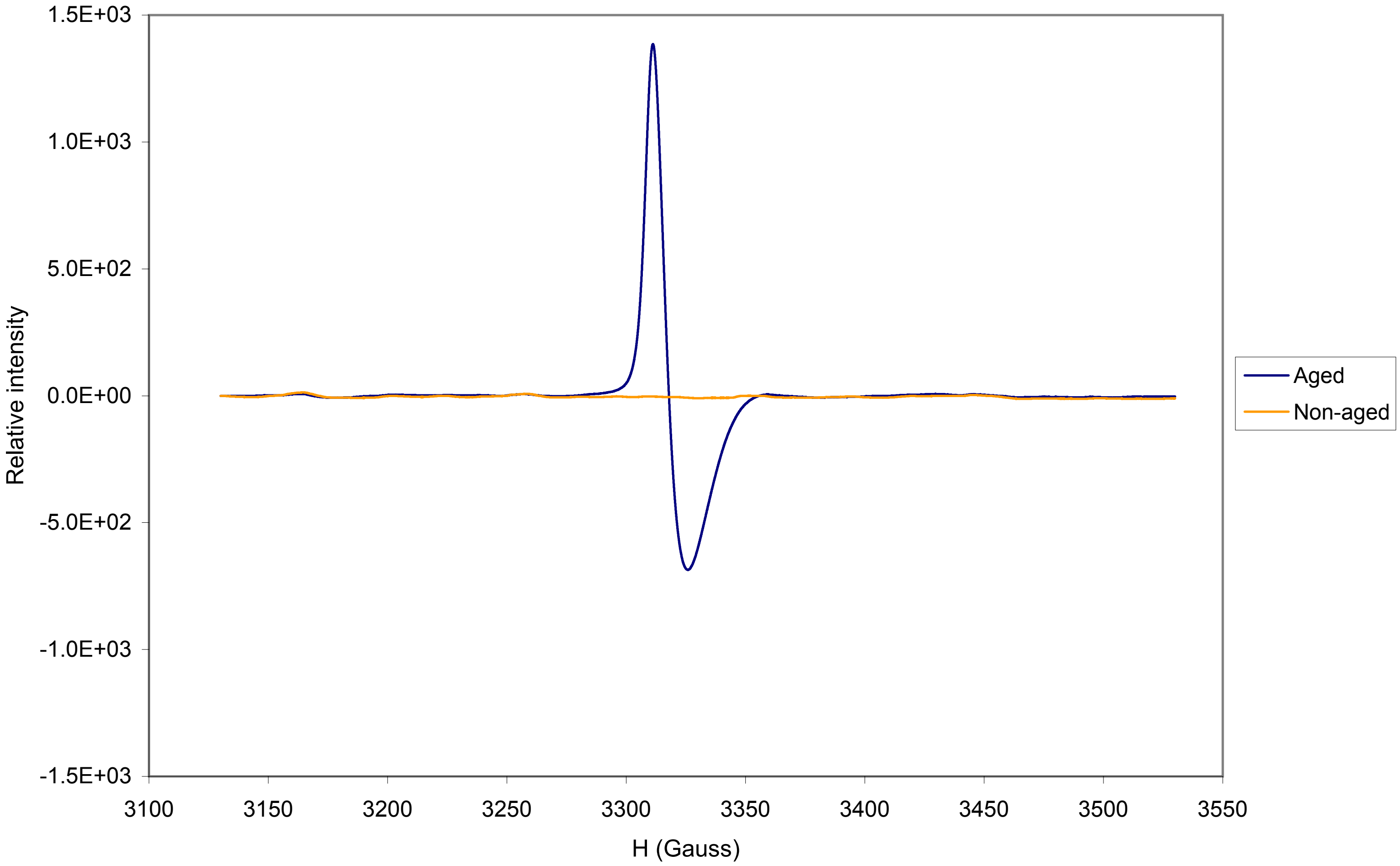


Figure 5.21: ESR spectrum of RPVR before aging and after aging at 220 °C for about 23.5 hours .

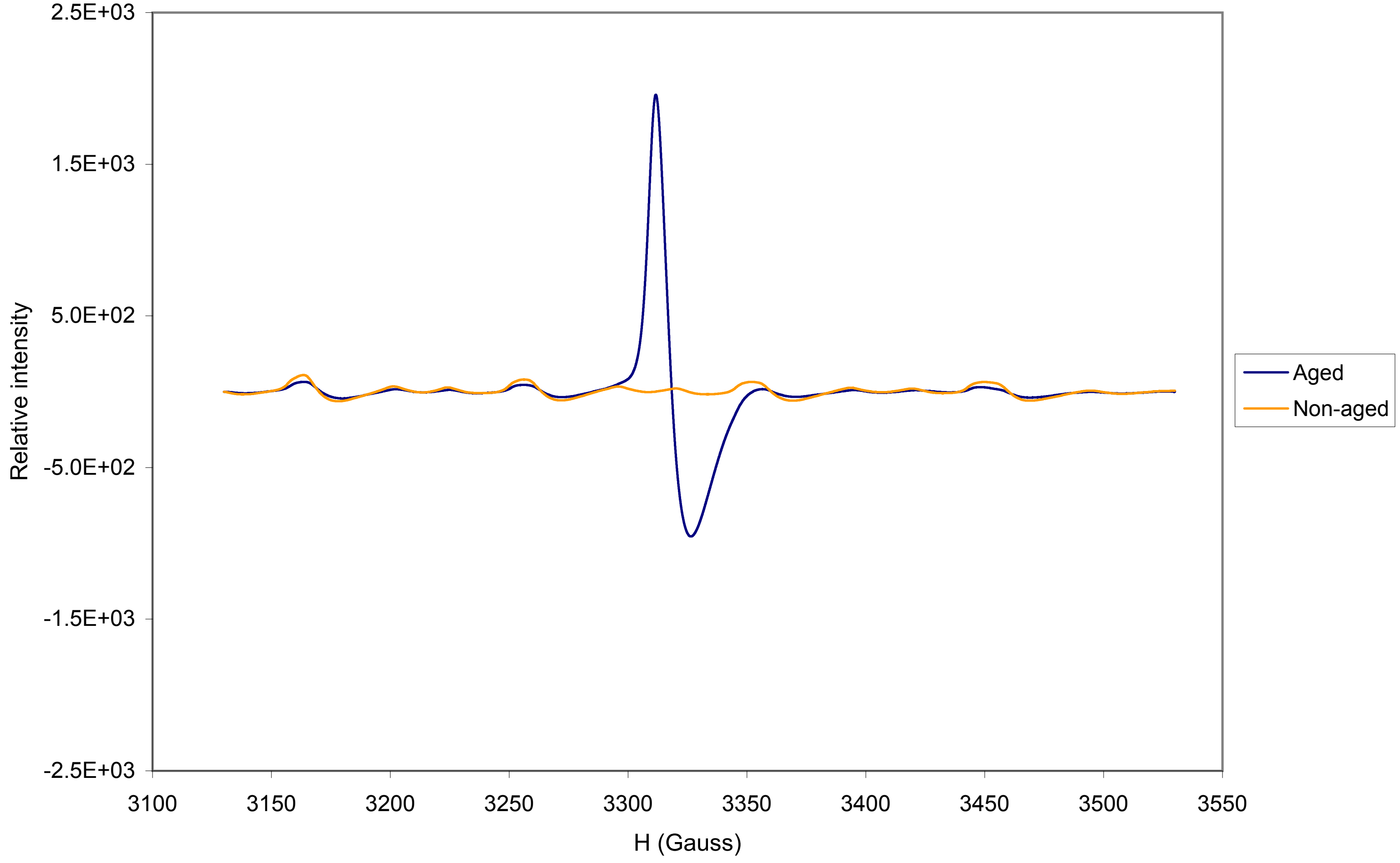


Figure 5.22: ESR spectrum of NPVB before aging and after aging at 220 °C for about 23.5 hours .

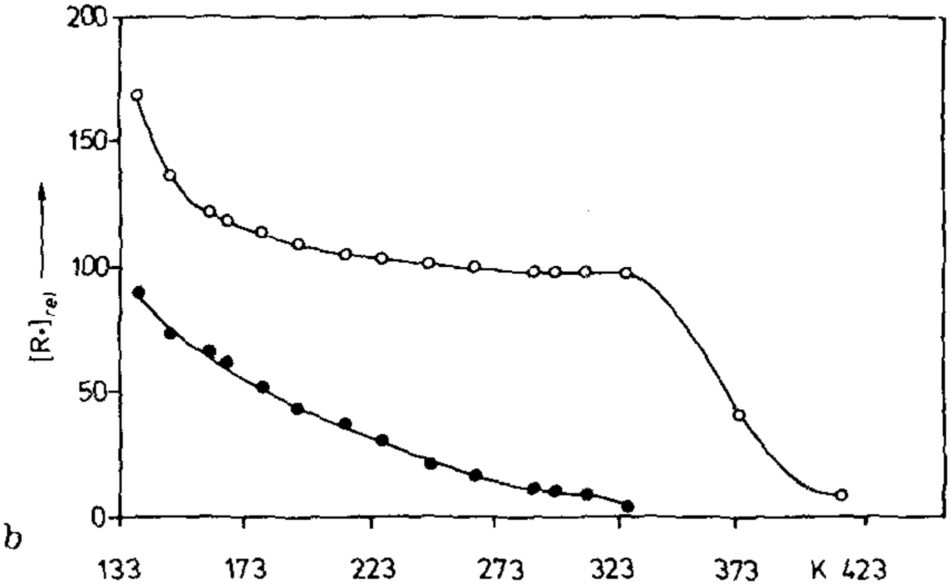


Figure 5.23:Free radical decay calculated from ESR spectra: (•) attributed to alkyl radical and (o) attributed to polyenyl radical.

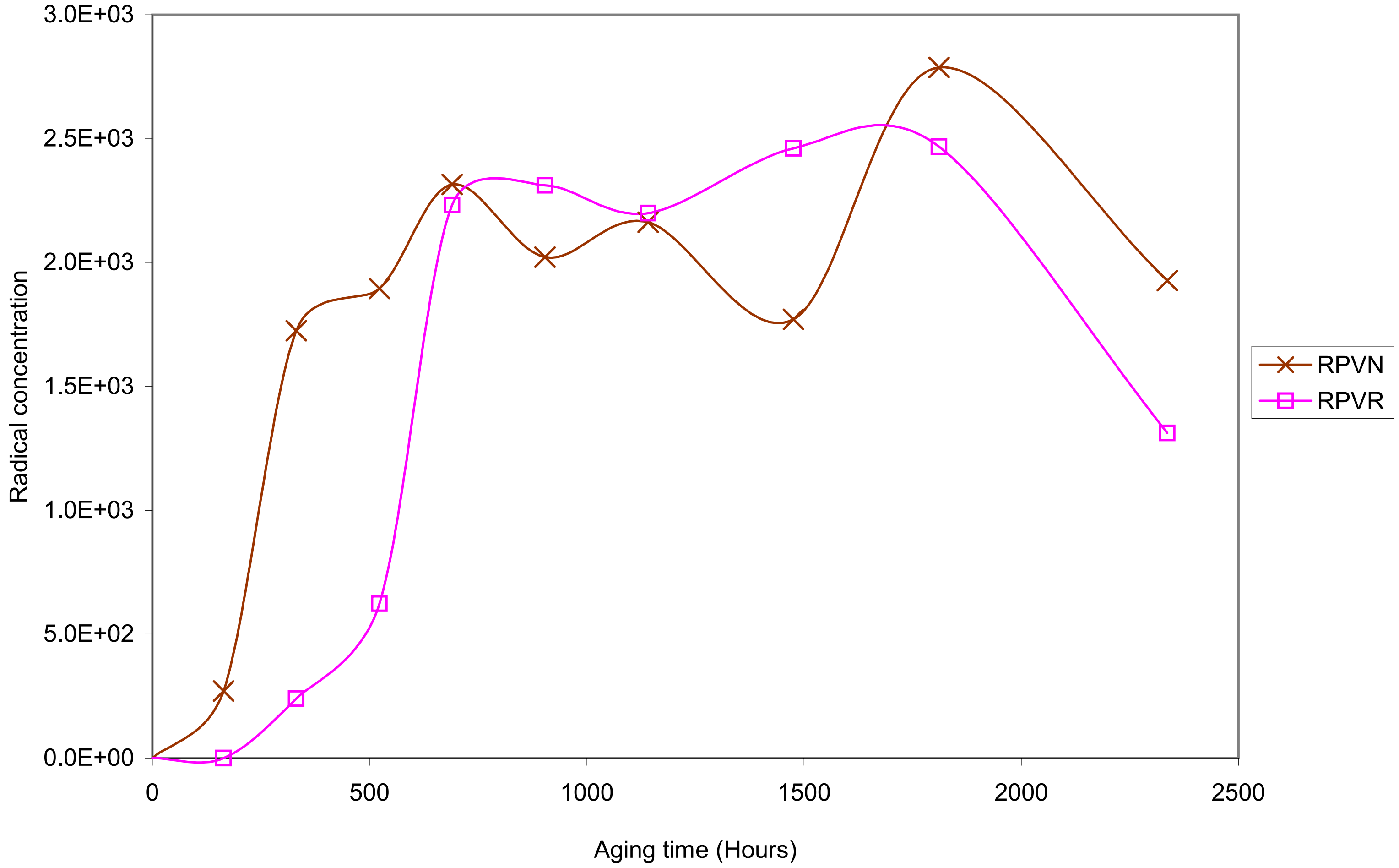


Figure 5.24: Concentration of polyene radicals during aging at 130 °C for PVC samples.

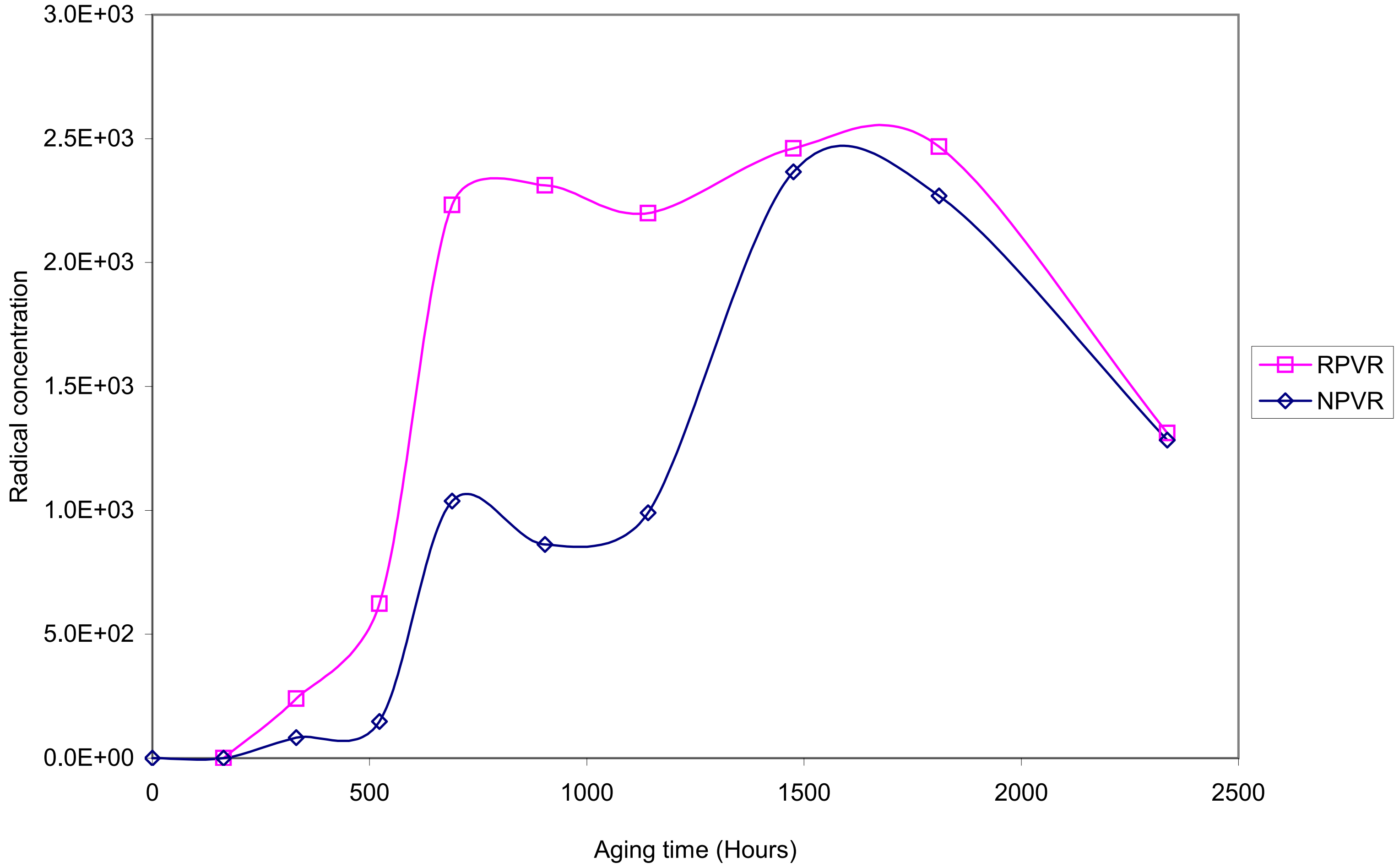


Figure 5.25: Concentration of polyene radicals during aging at 130 °C for PVC samples.

It can be observed in Figure 5.25 that free radical formation from the raw PVC insulation is higher than that of the manufactured PVC insulation at the beginning of the aging time. The manufacturing process is expected to partially deform the original materials by removing amount of HCL molecules. The more the removal of the very corrosive HCL, the less polyene macro-radicals is expected to be formed from the manufactured PVC insulation. The similarity in ESR-peak height of the investigated samples after about 1500 hours of aging time at 130 °C may be correlated with the similarity of aged material and certain the ESR results.

A small broad singlet ESR spectrum has been observed during vacuum irradiation of polyethylene at 77 K [117, 118], Figure 5.26. Figures 5.27 and 5.28 show ESR spectrum observed during thermal aging of XLPE insulations. This singlet ESR-Line is similar to the one reported in PVC samples that is related to a conjugated polyene structure of the macro-radical.

Figure 5.29 shows the concentrations of polyene radicals formed in XLPE insulations during thermal aging. It can be observed that the onset point of the raw XLPE insulation is higher than that of the manufactured XLPE insulation. The result in Figure 5.29 indicates also that the manufacturing XLPE insulation introduces more radicals than raw XLPE insulation.

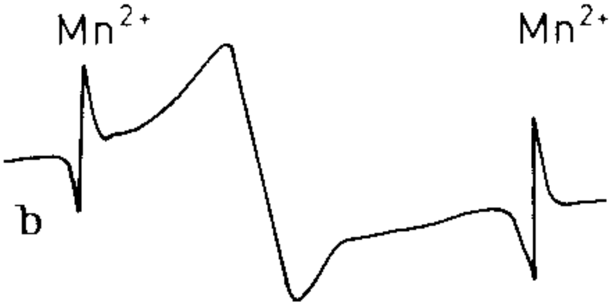


Figure 5.26: ESR spectrum of polyethylene UV-irradiated at 77 K and measured at 77 K, the separation between the two Mn^{2+} is 86.7 G.

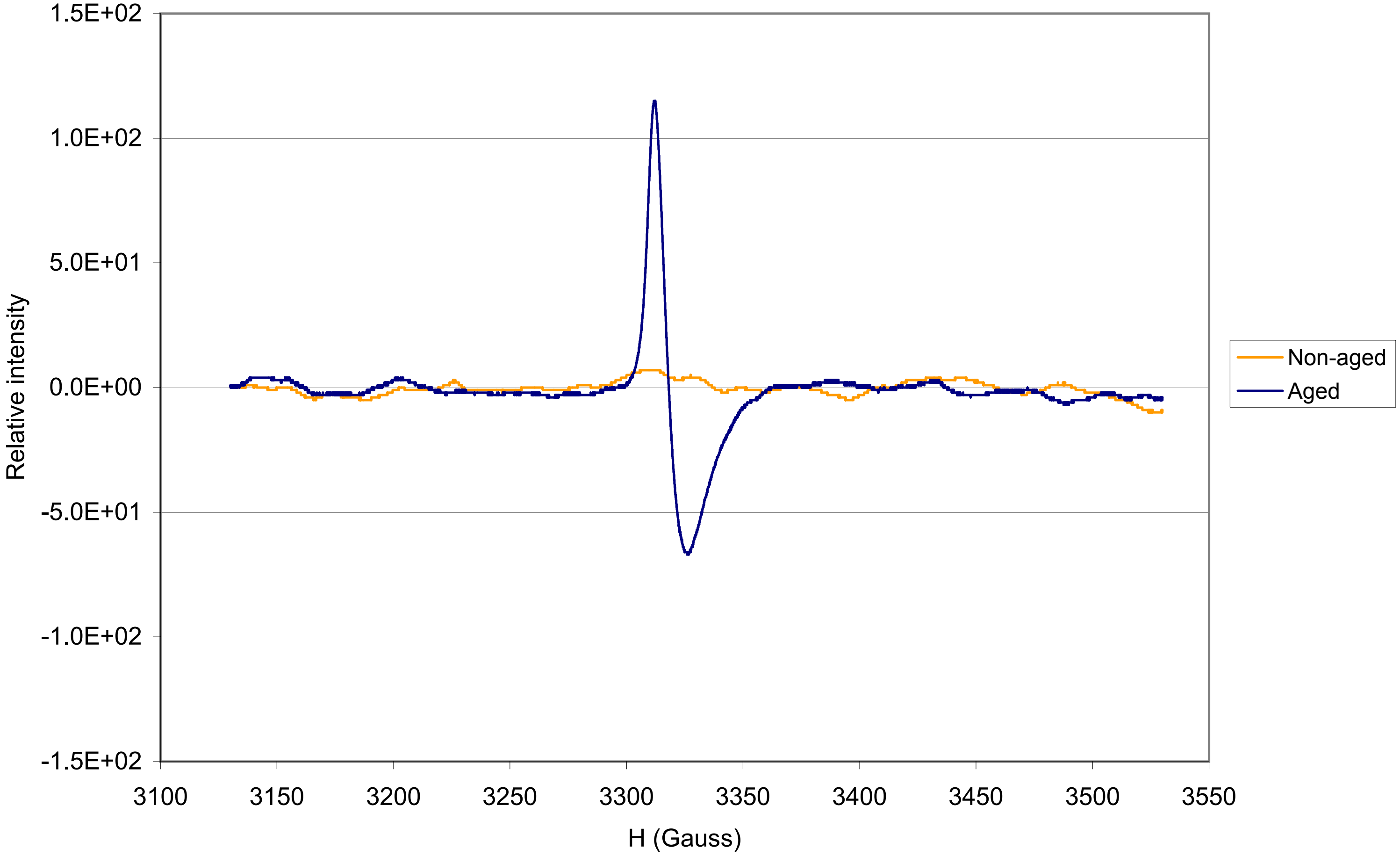


Figure 5.27: ESR spectrum of RXLN before aging and after aging at 220 °C for about 72 hours .

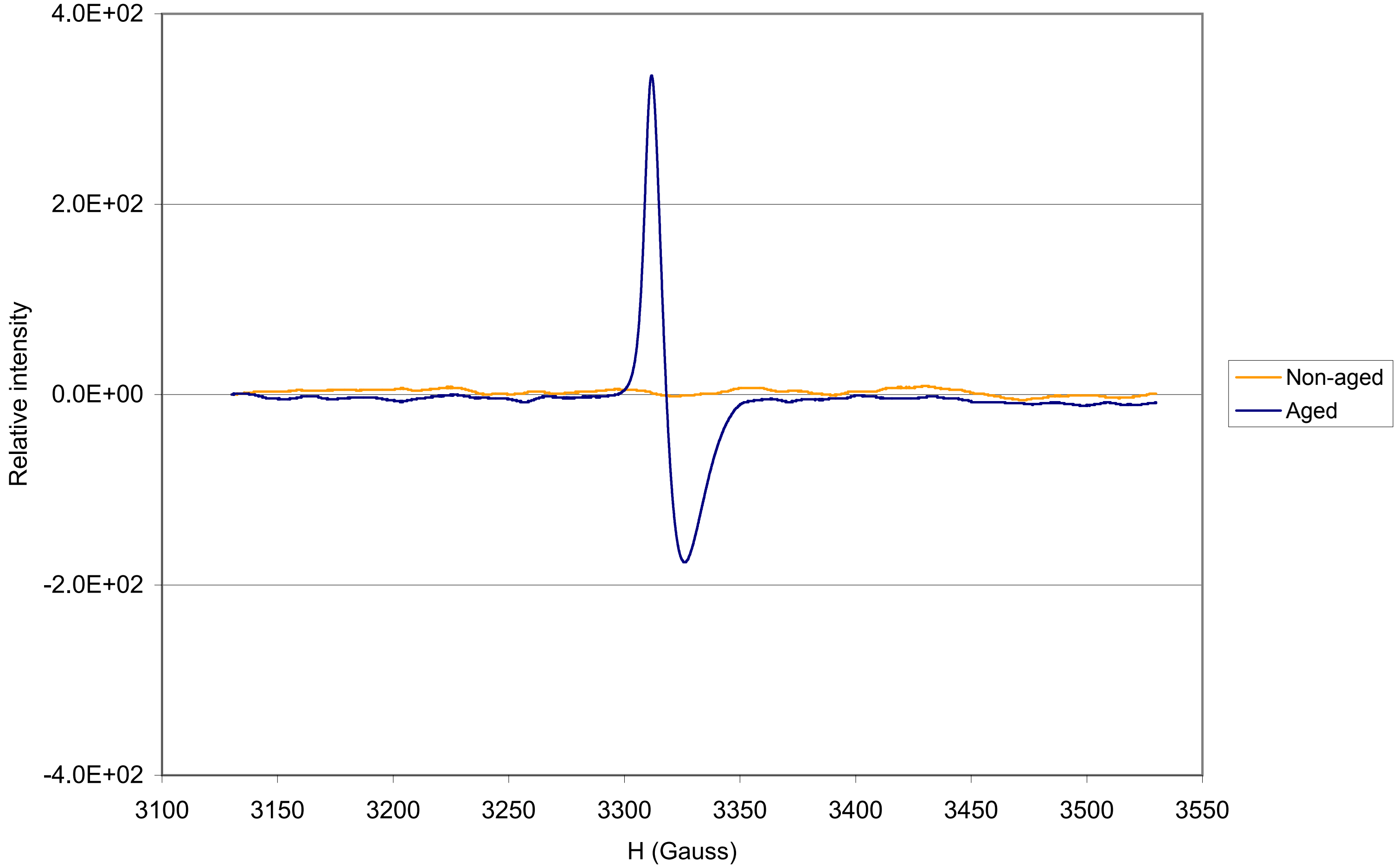


Figure 5.28: ESR spectrum of NXLN before aging and after aging at 220 ^{o}C for about 23 hours.

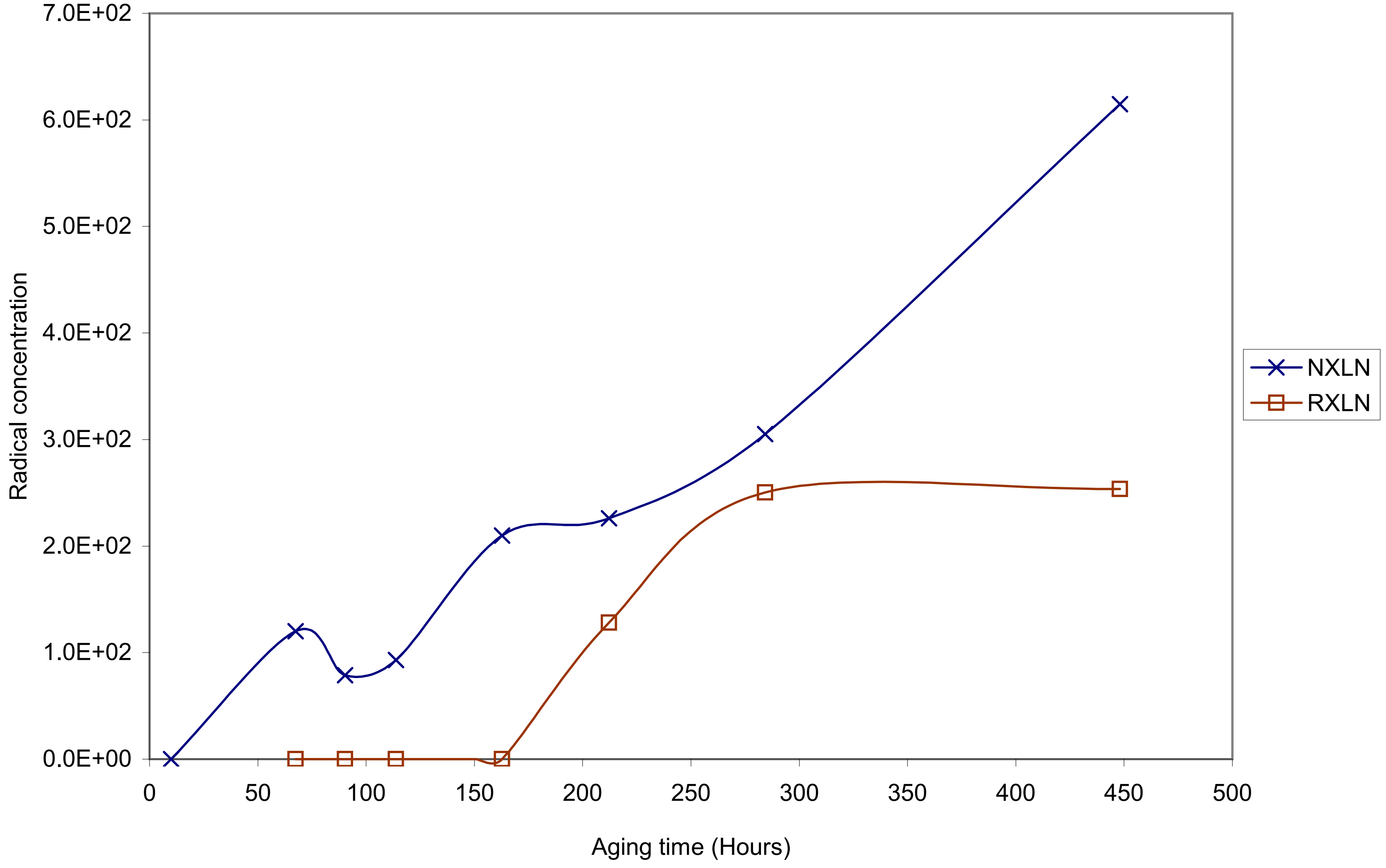


Figure 5.29: Concentration of polyene radicals during aging at 170 °C for XLPE samples.

6.3 LIFE-TIME CURVE

6.3.1 PVC

The failure points of PVC insulations at different test temperatures based on failure criteria of 0.5% weight loss are shown on Figures 5.30 to 5.34. The parameters of the thermal life equation are calculated based on the results of weight loss test.

On the other hand, Figures 5.35 to 5.39 show the failure points of PVC insulations depending on the ESR test results. Another parameters of thermal life equation are found based on the ESR test. The lifetime curves of the tested PVC insulating materials are shown on Figure 5.40 to Figure 5.44.

6.3.2 XLPE

Figures 5.45 and 5.46 show the failure points of XLPE insulations at different test temperatures based on failure criteria of 0.5% weight loss. However, Figures 5.47 and 5.48 show the failure points of XLPE insulations depending on the ESR test results. The parameters of the thermal life equation are calculated based on the results of weight loss test and the results of ESR test. Figures 5.49 and 5.50 show the lifetime plots of the tested XLPE insulating materials. Also,

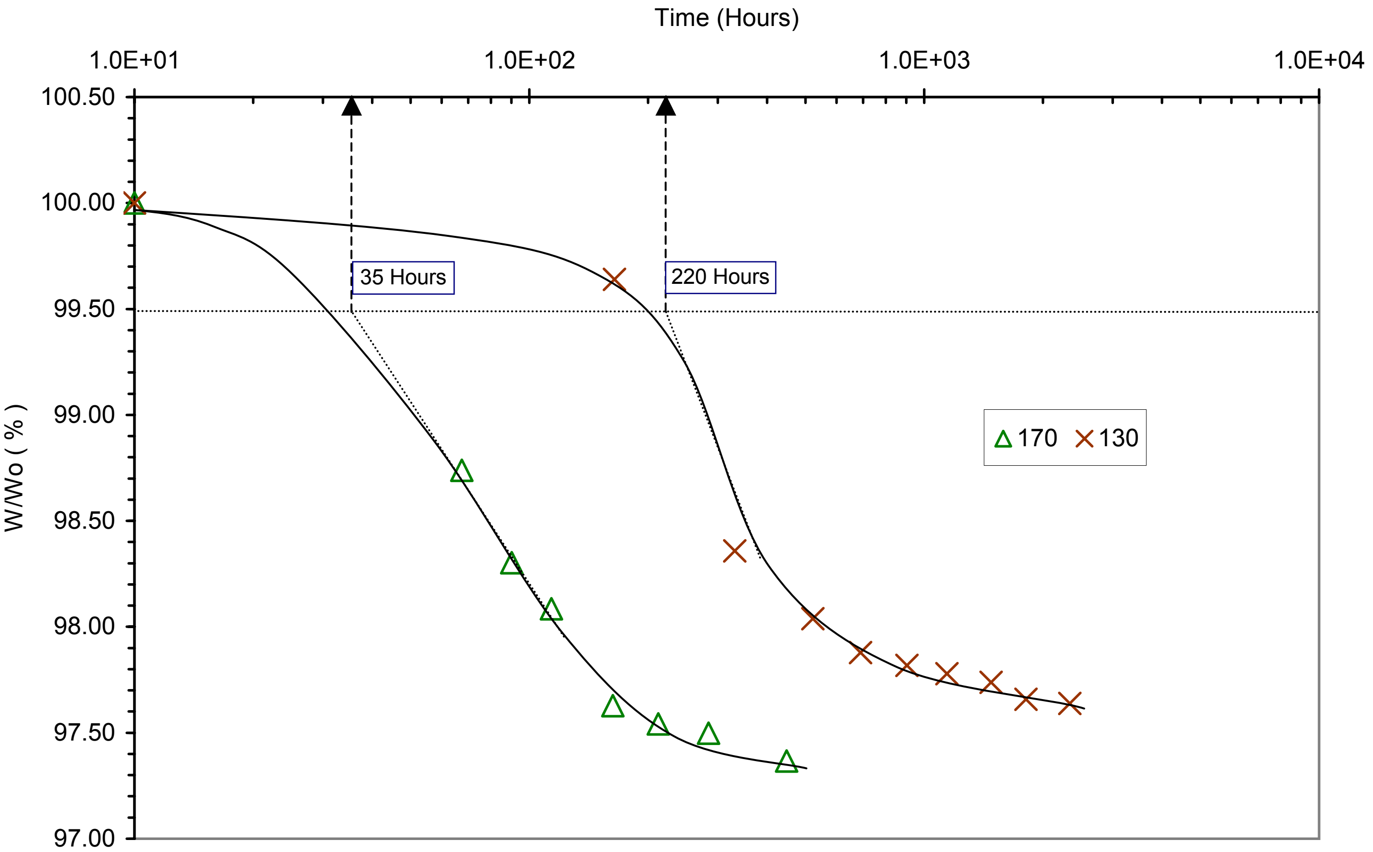


Figure 5.30: Failure point of RPVN based on weight test.

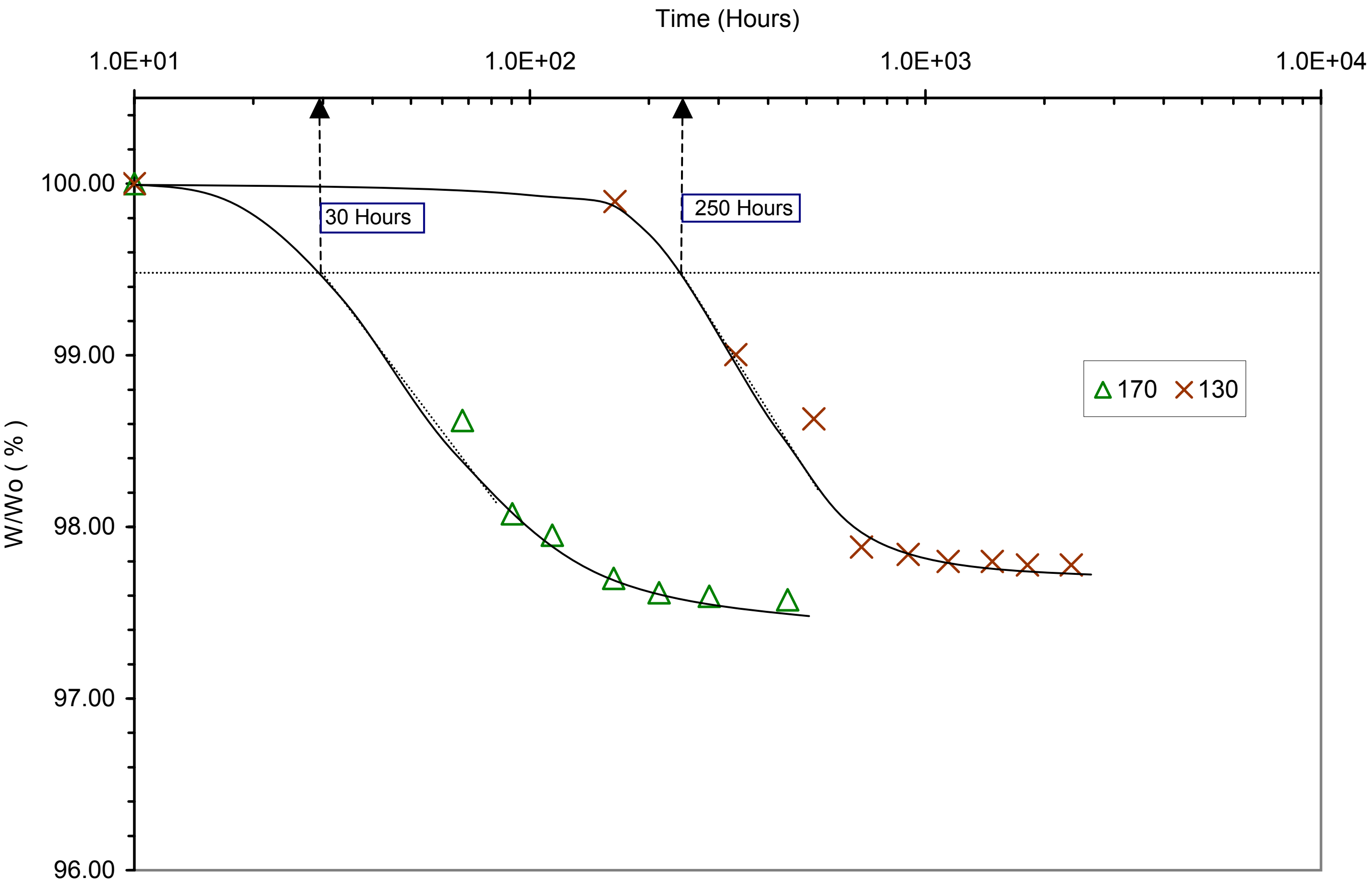


Figure 5.31: Failure point of RPVB based on weight test.

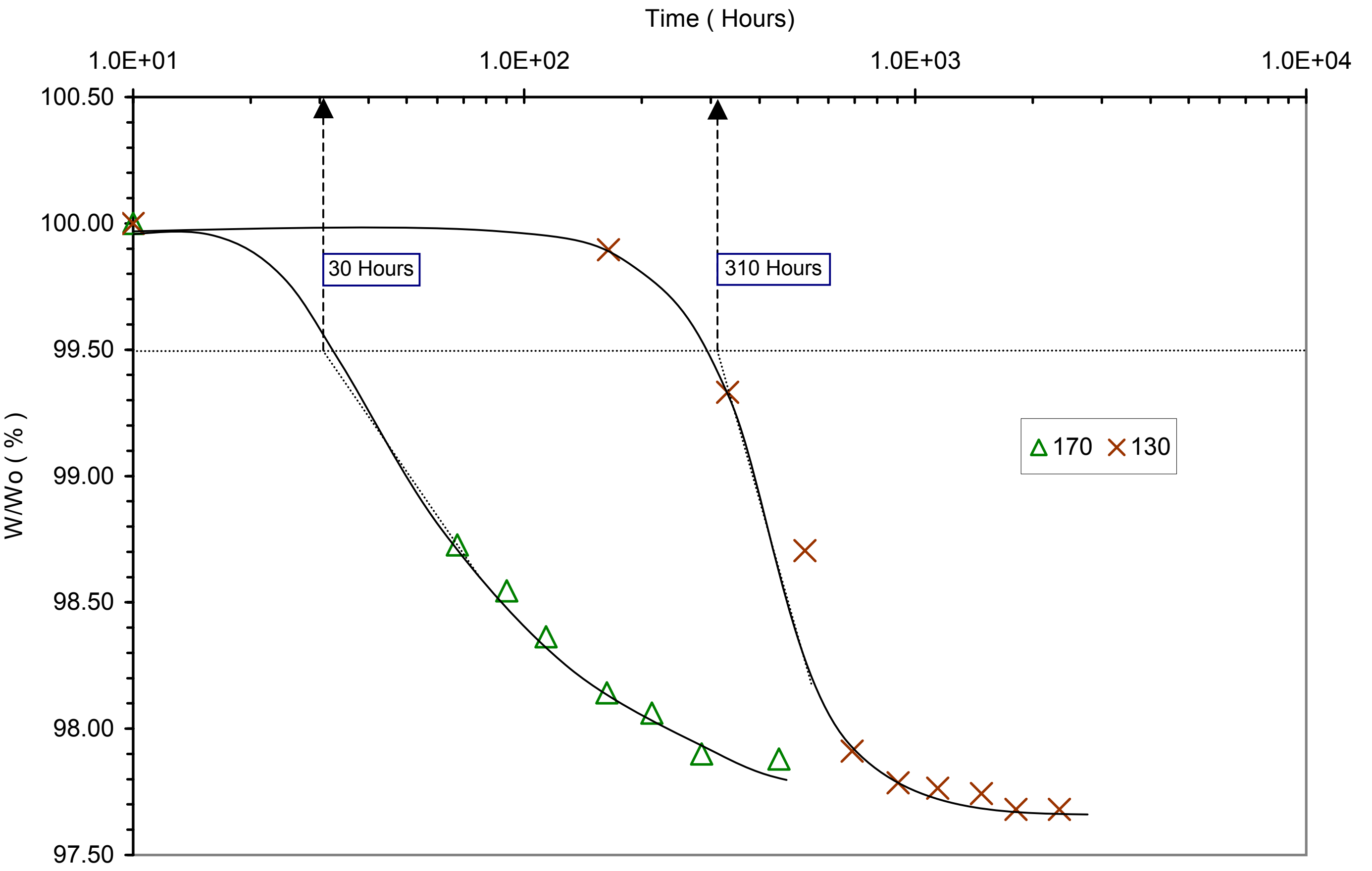


Figure 5.32: Failure point of RPVR based on weight test.

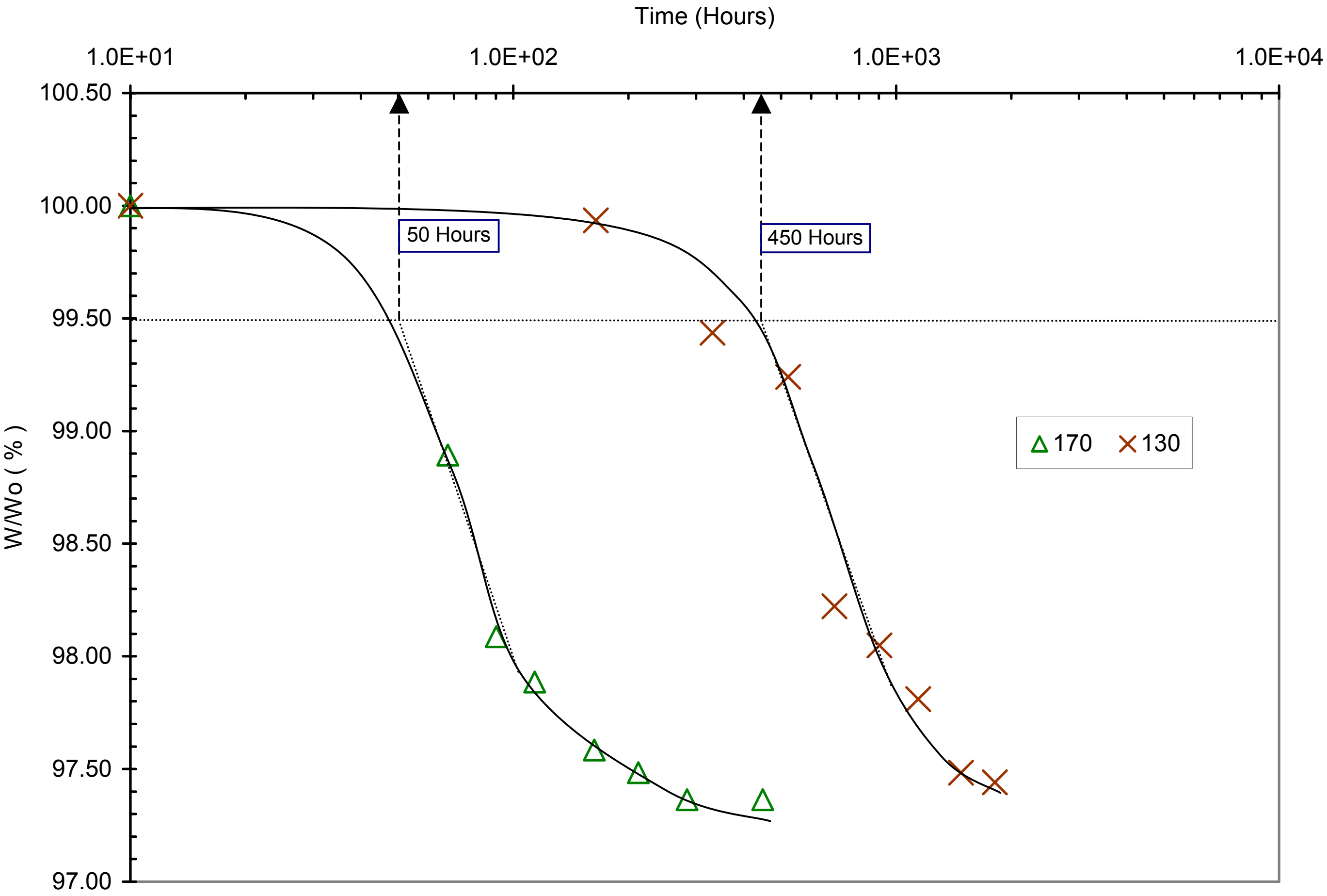


Figure 5.33: Failure point of NPVR based on weight test.

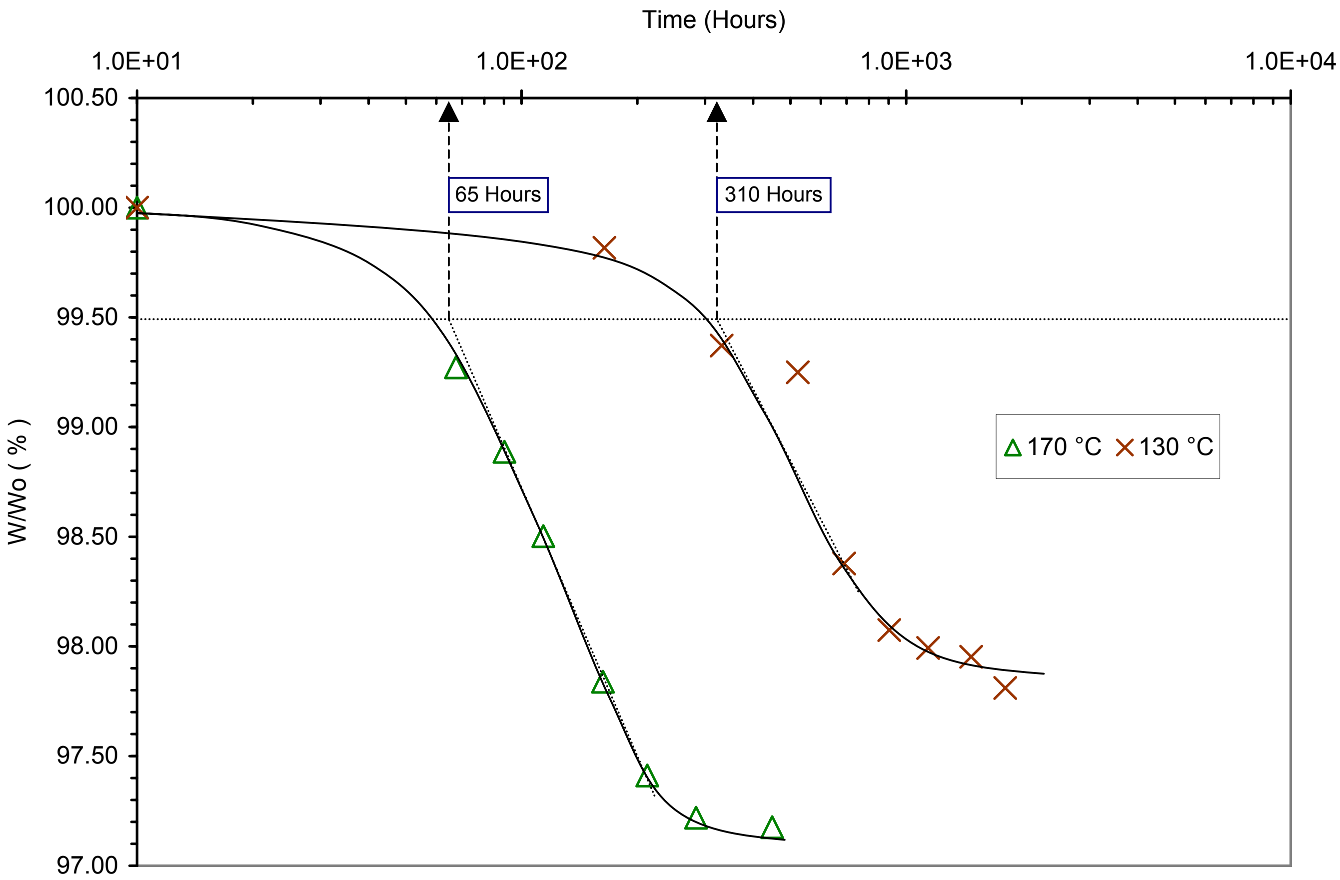


Figure 5.34: Failure point of NPVB based on weight test.

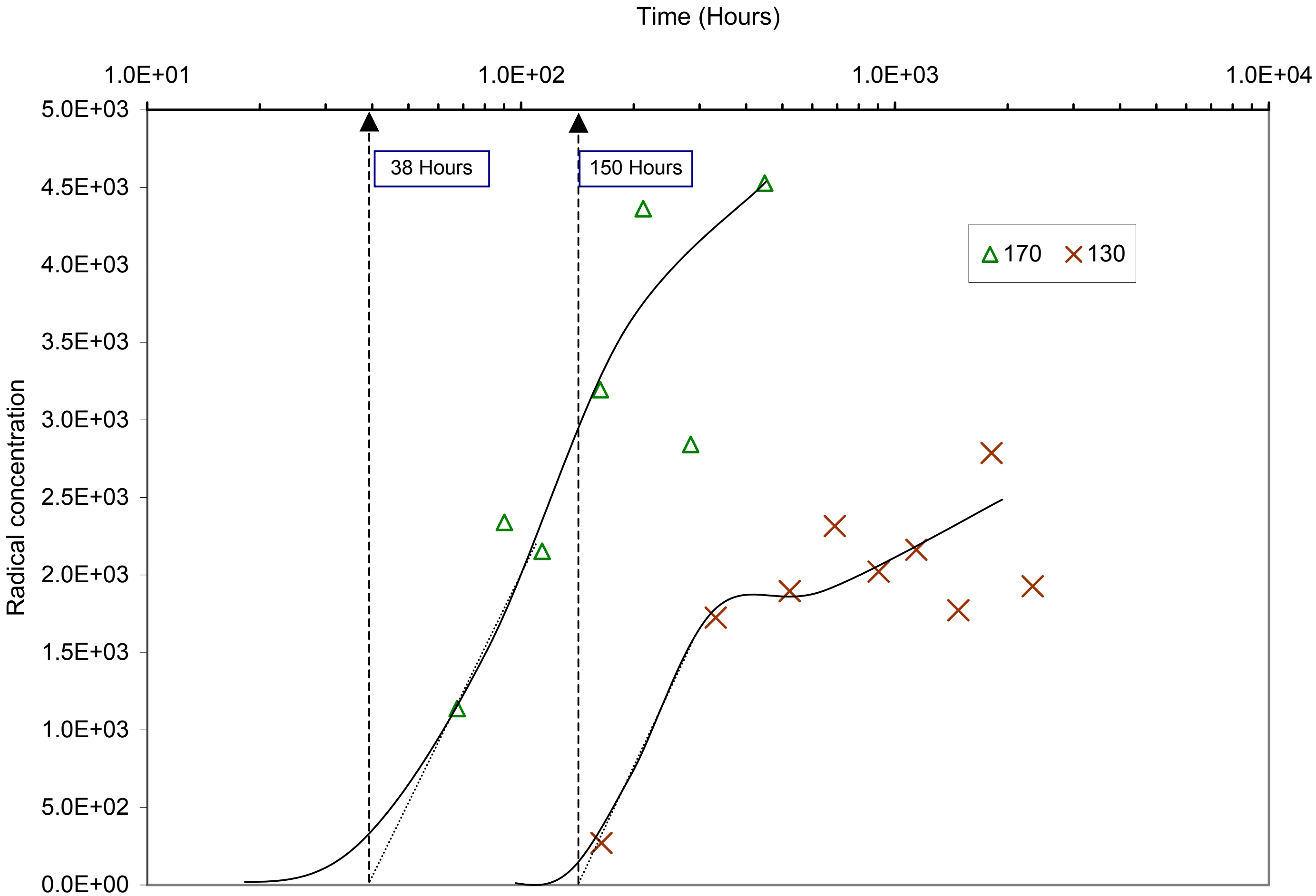


Figure 5.35: Failure point of RPVN according to ESR test.

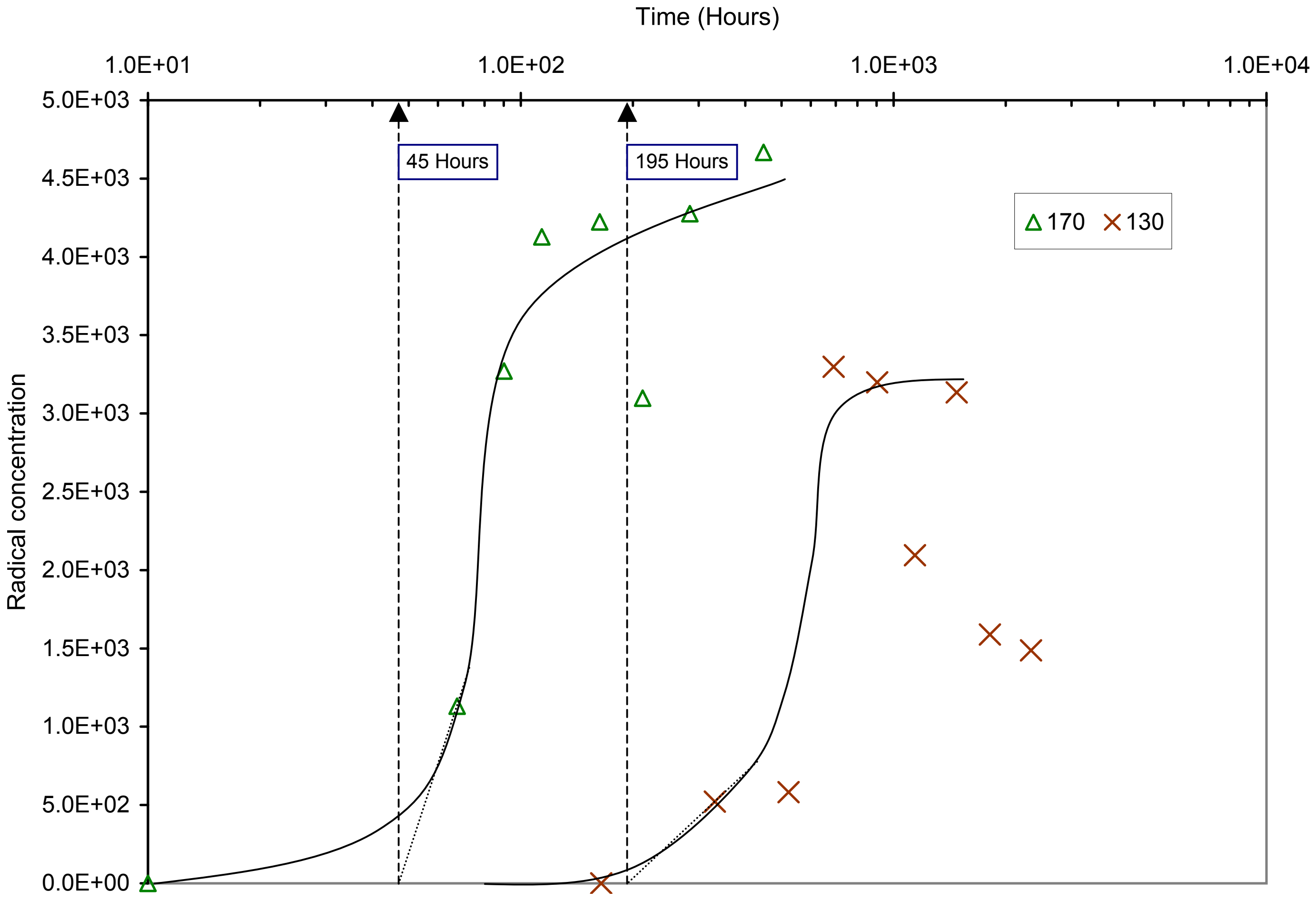


Figure 5.36: Failure point of RPVB according to ESR test.

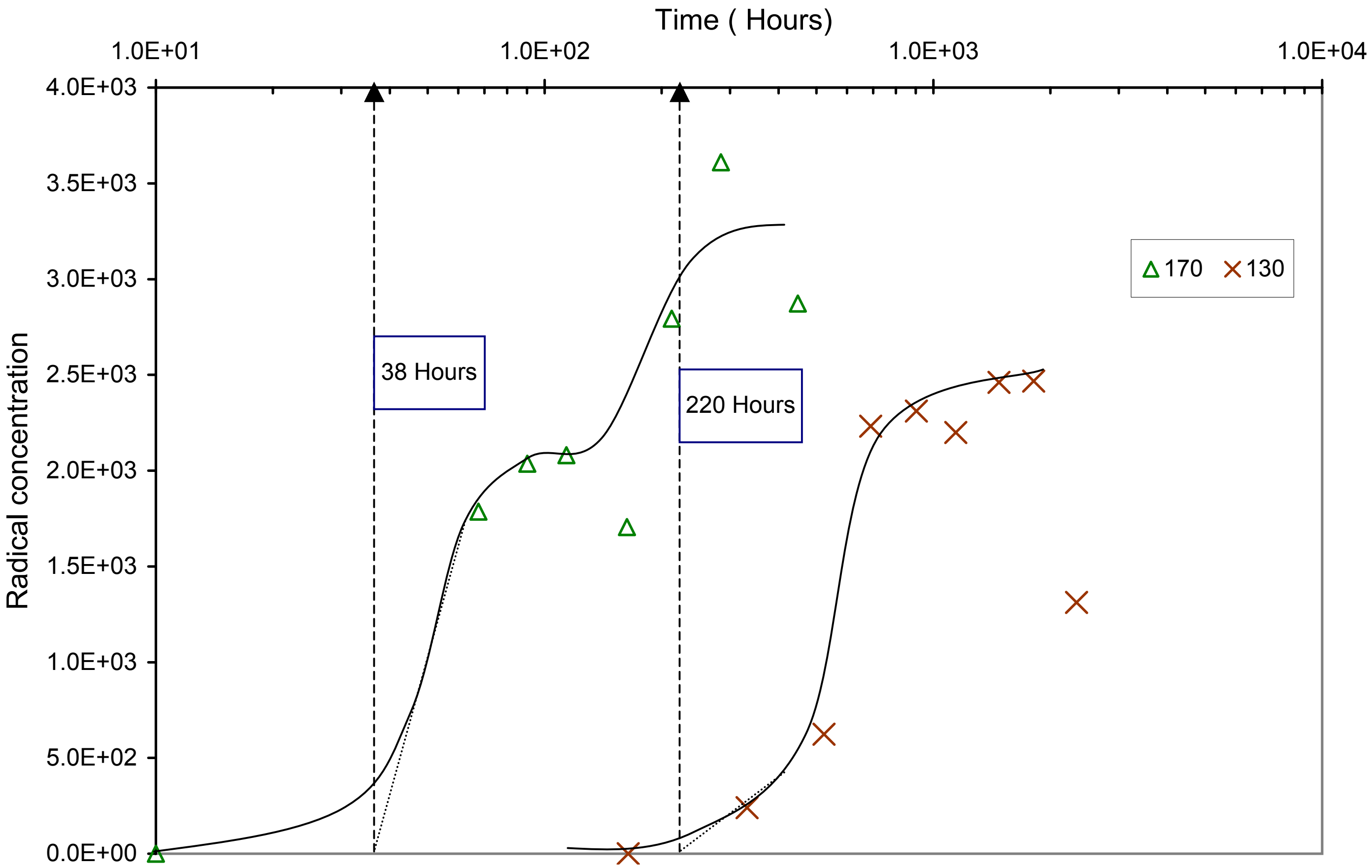


Figure 5.37: Failure point of RPVR according to ESR test.

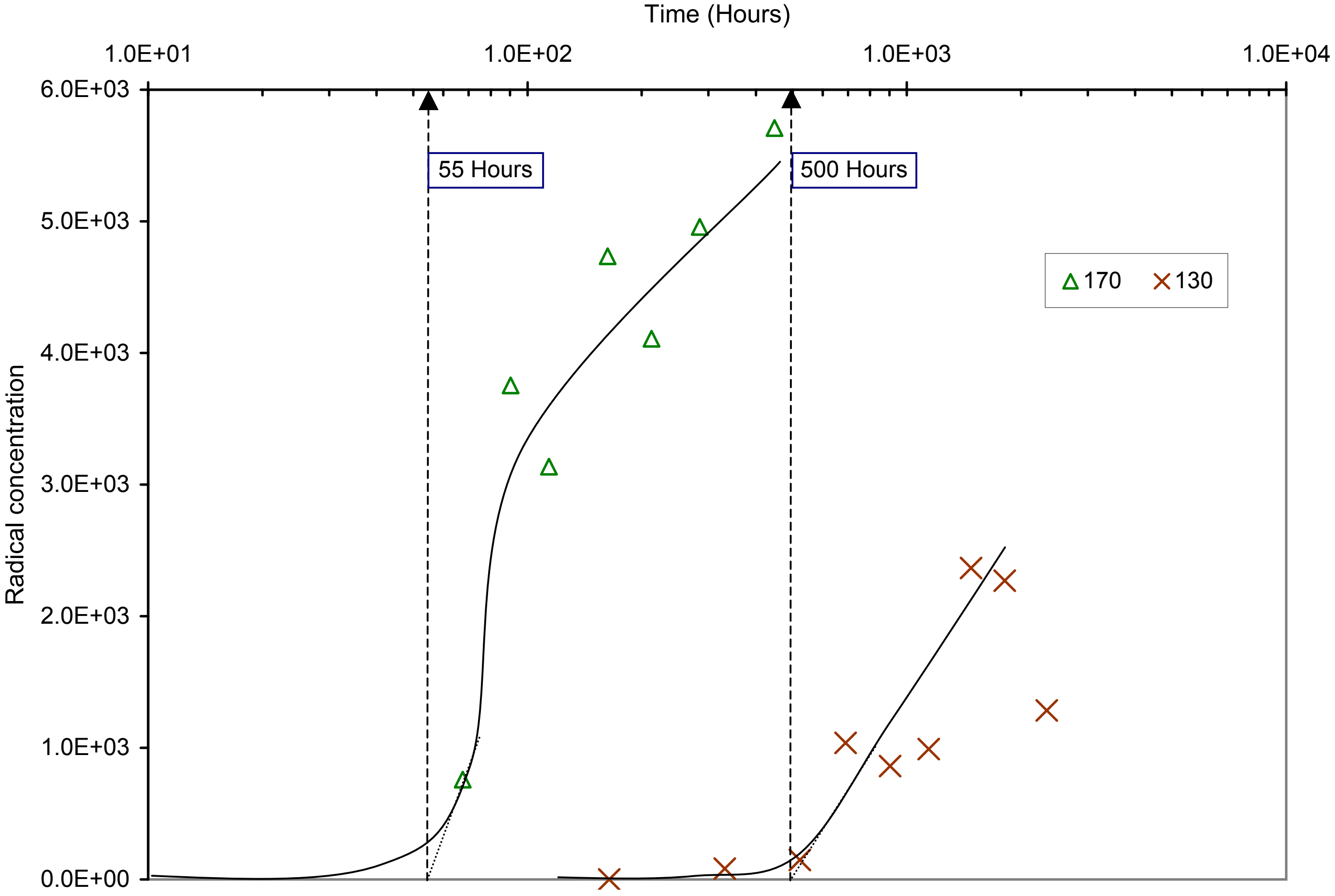


Figure 5.38: Failure point of NPVR according to ESR test.

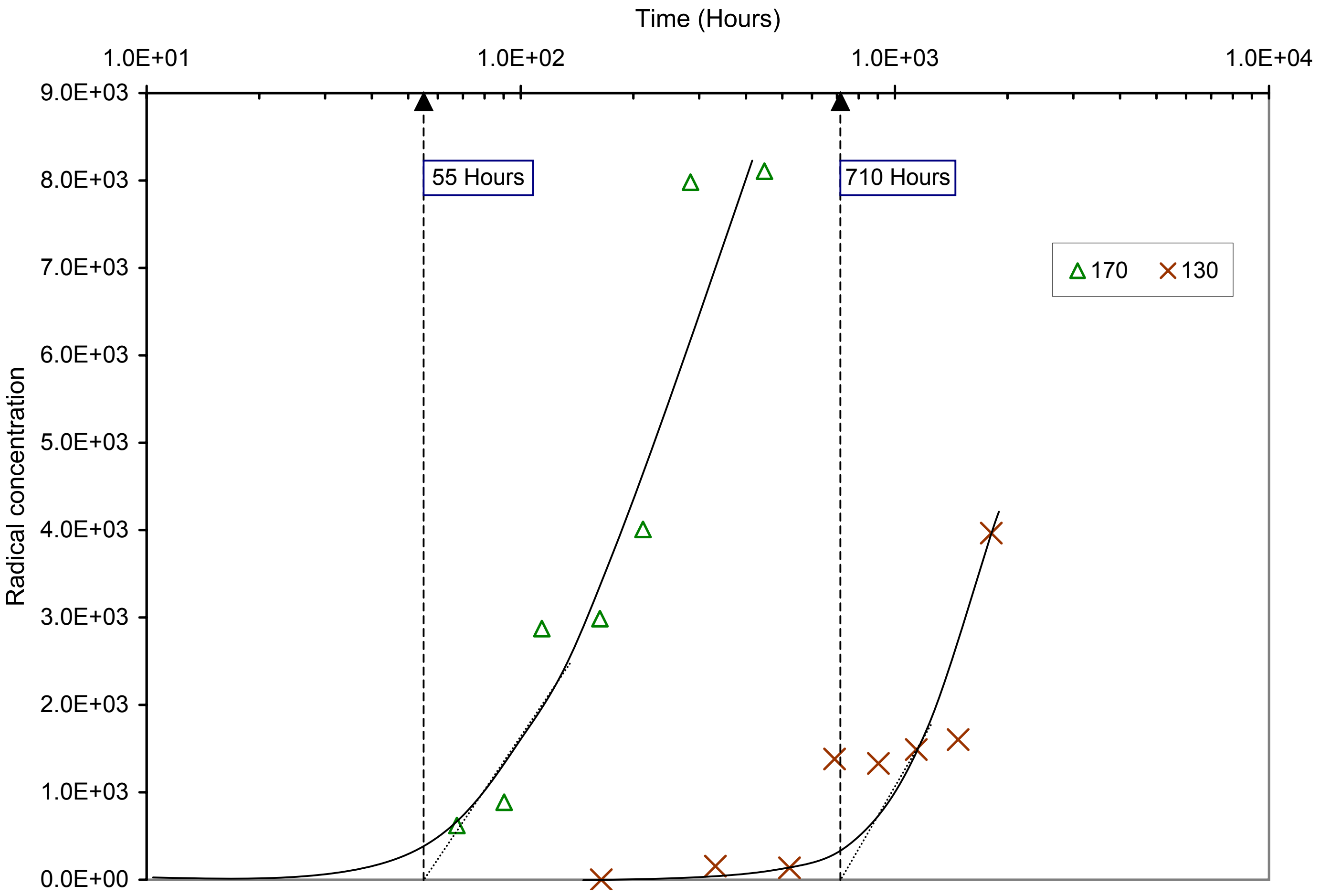


Figure 5.39: Failure point of NPVB according to ESR test.

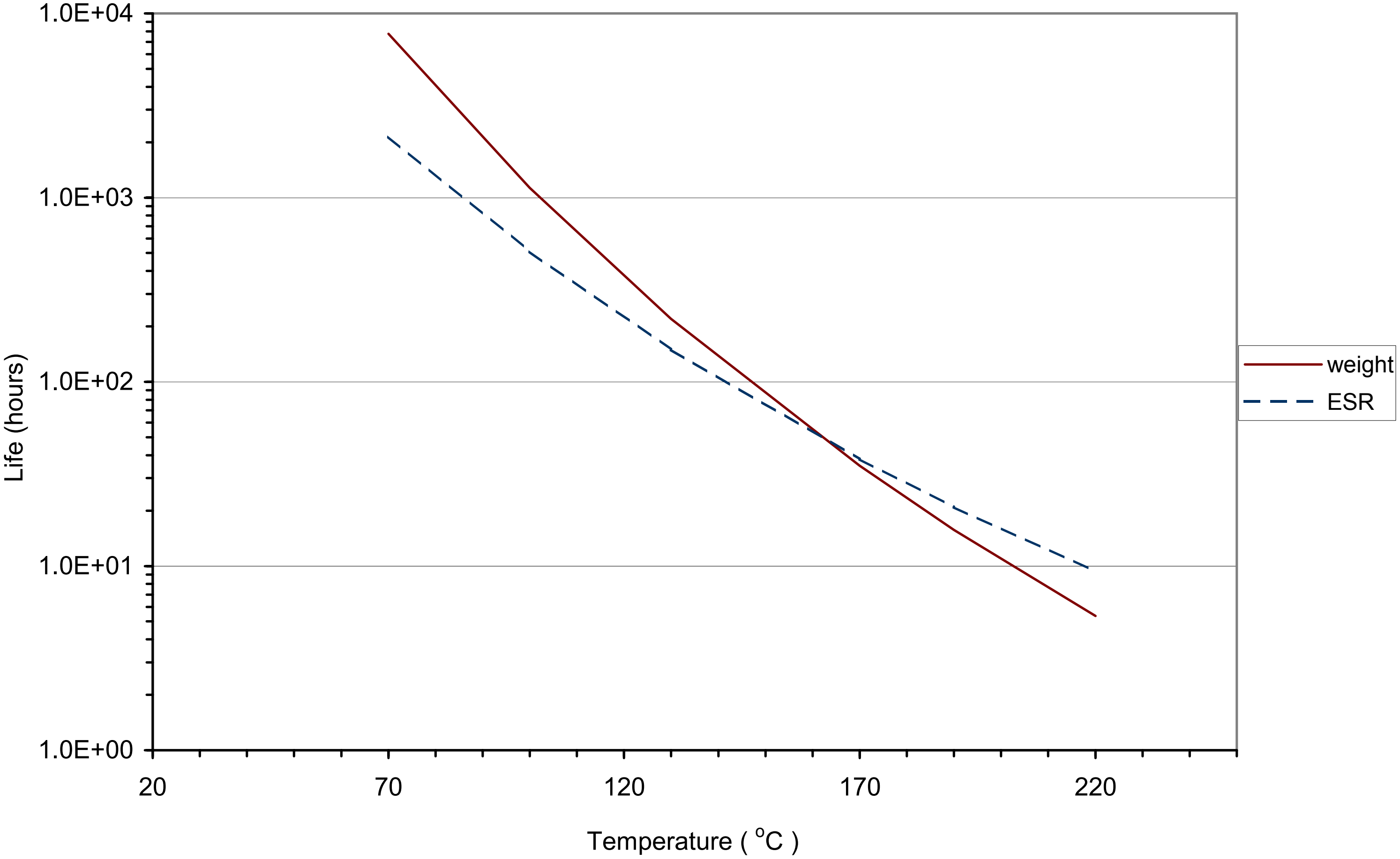


Figure 5.40: Thermal life-time of RPVN.

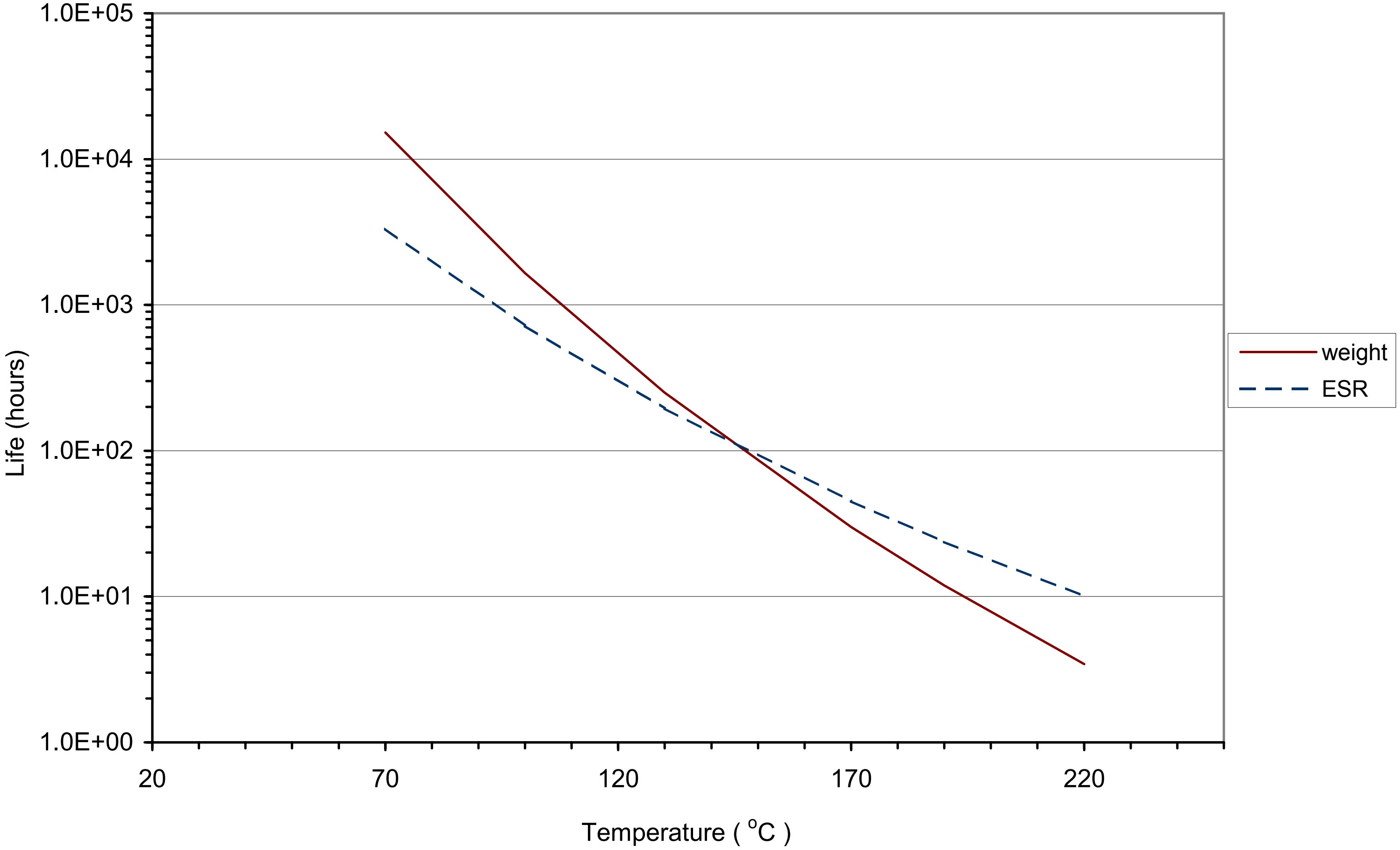


Figure 5.41: Thermal life-time of RPVB.

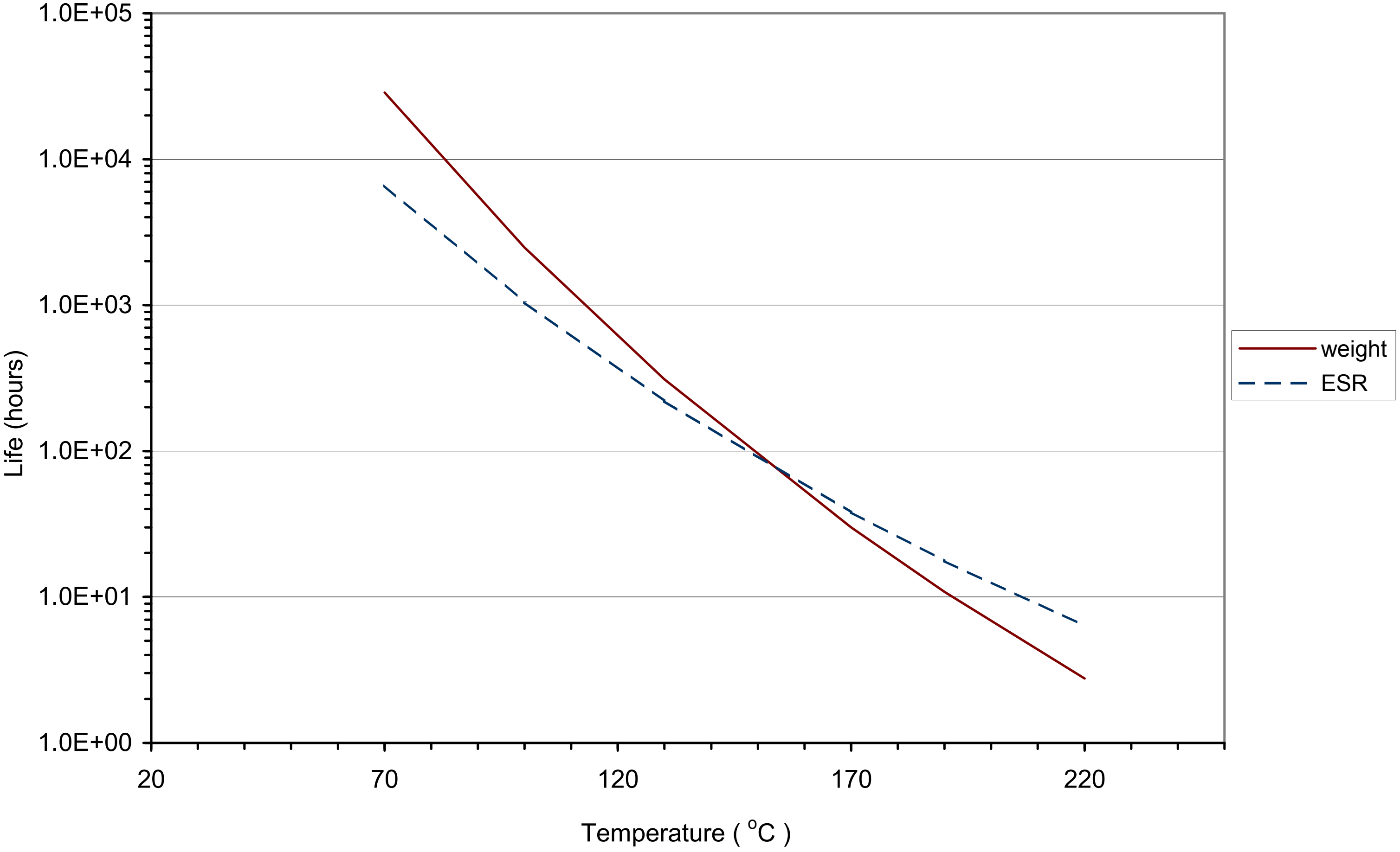


Figure 5.42: Thermal life-time of RPVR.

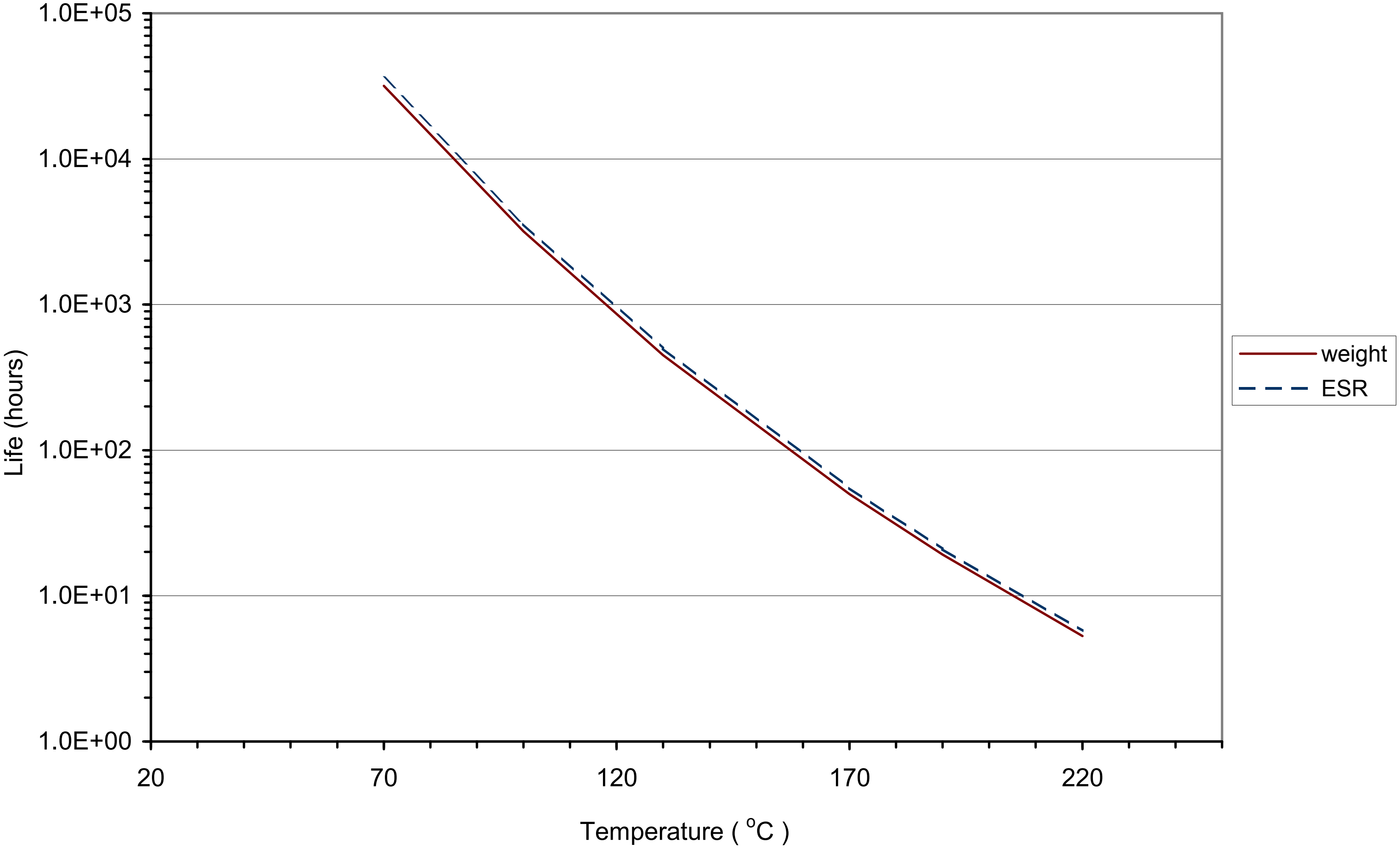


Figure 5.43: Thermal life-time of NPVR.

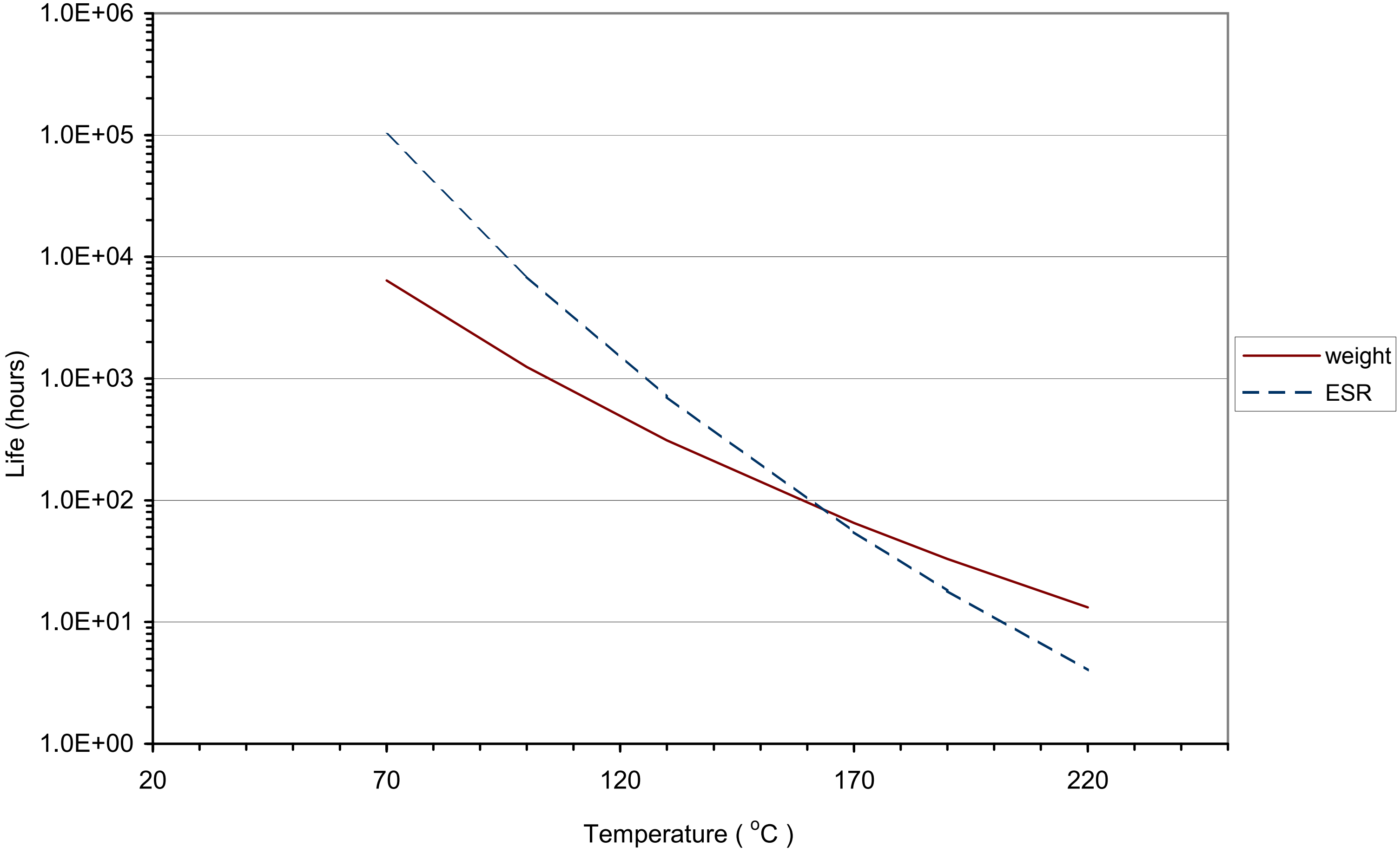


Figure 5.44: Thermal life-time of NPVB.

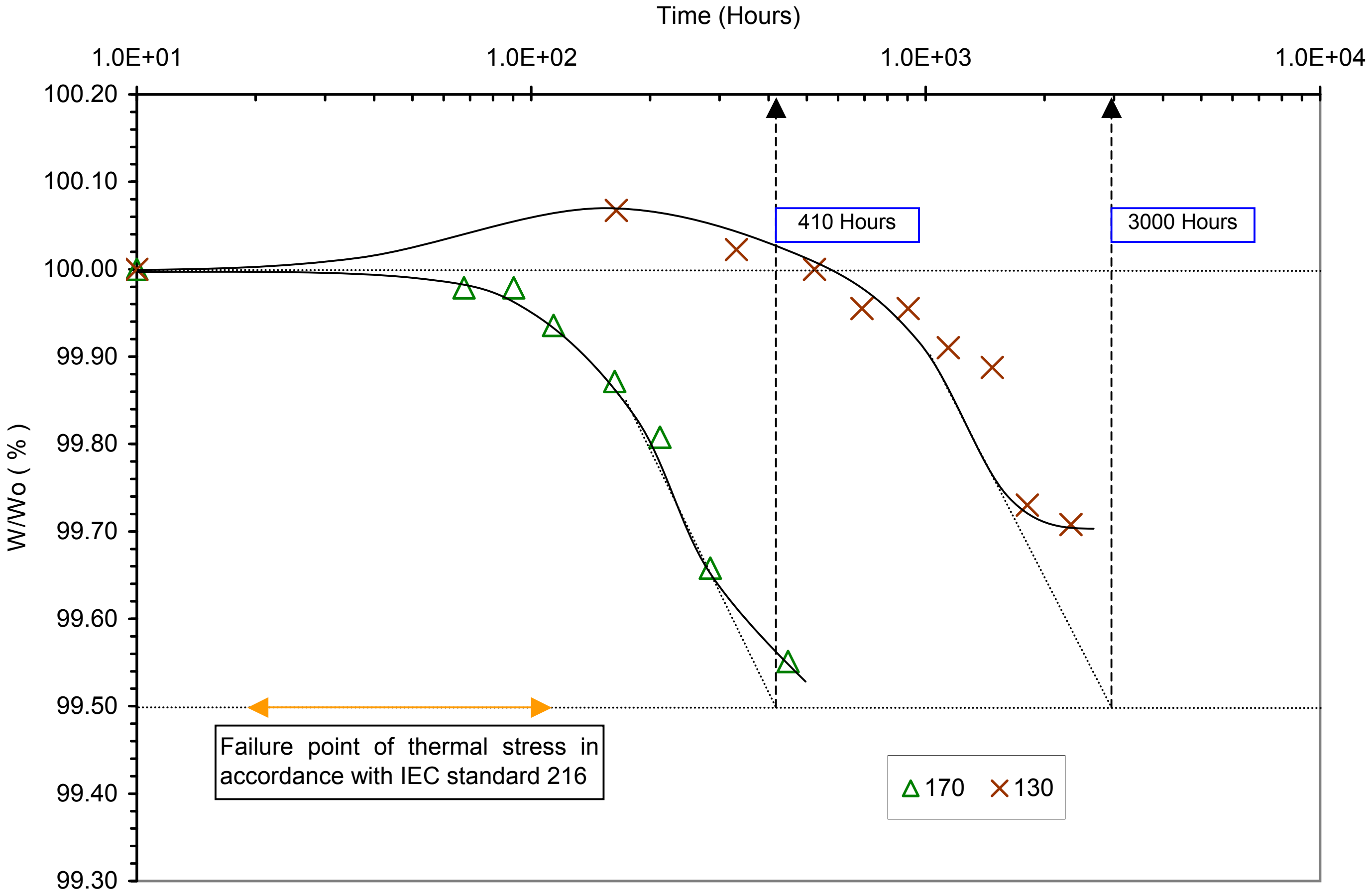


Figure 5.45: Failure point of RXLN based on weight test.

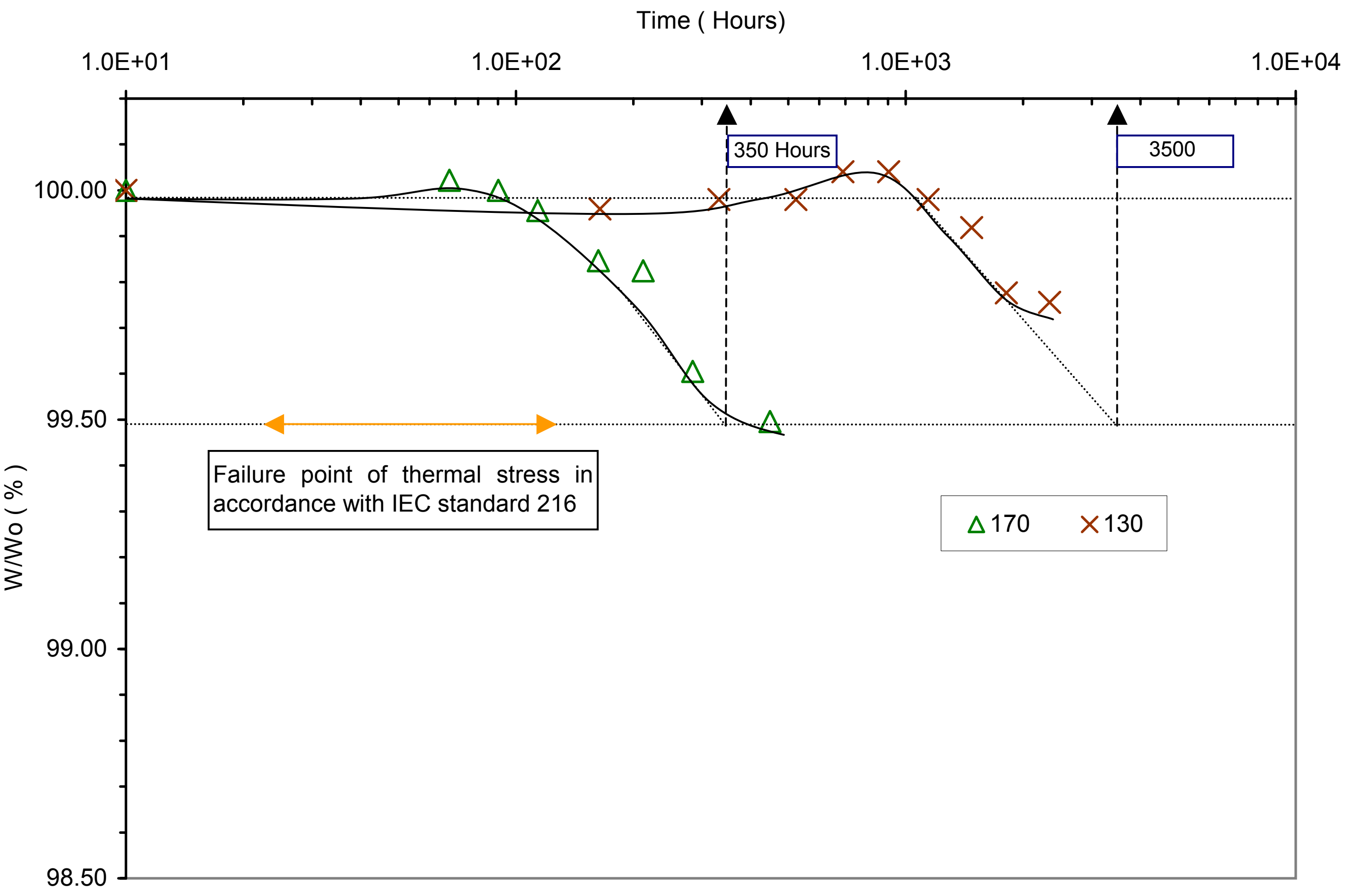


Figure 5.46: Failure point of NXLN based on weight test.

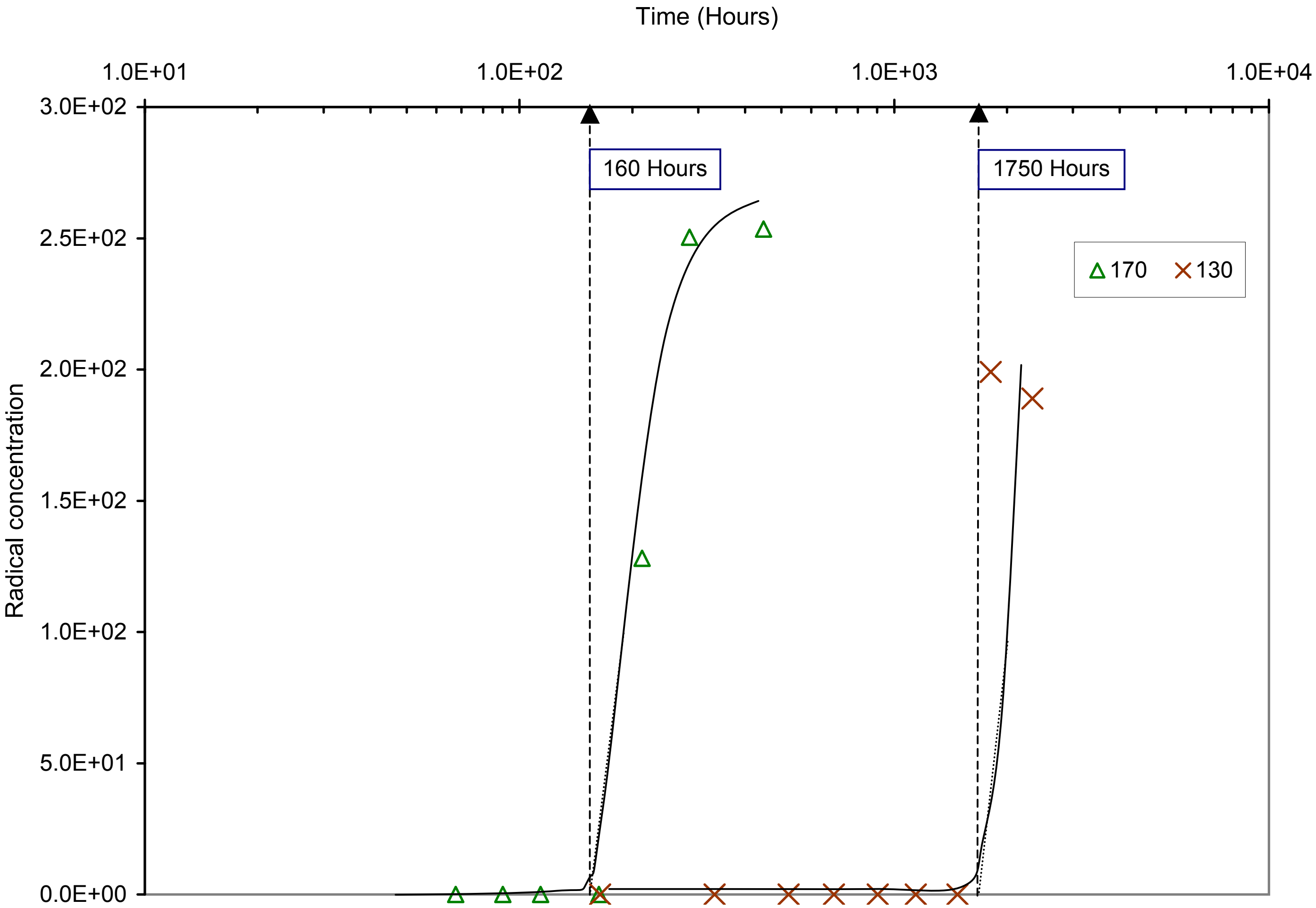


Figure 5.47: Failure point of RXLN according to ESR test.

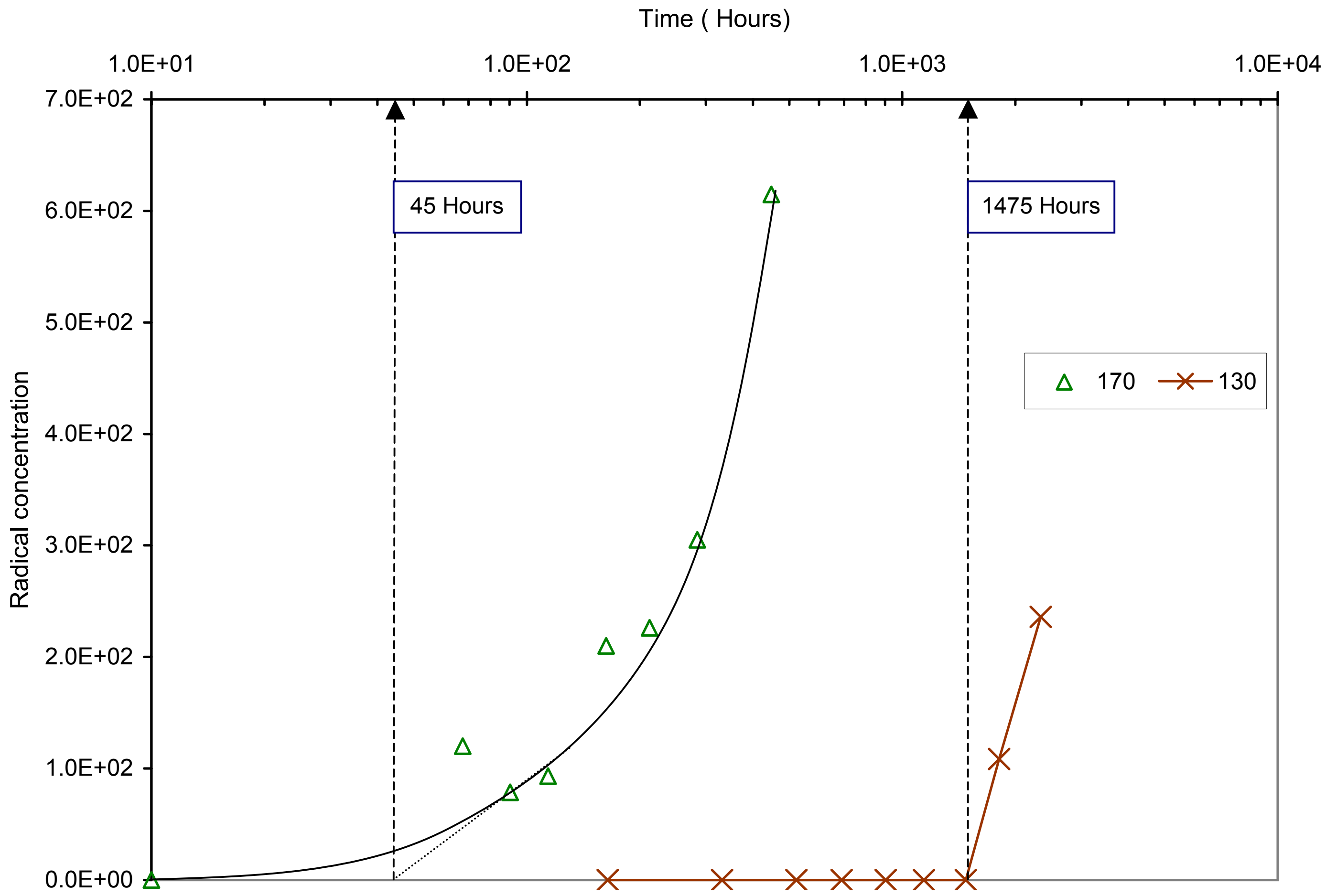


Figure 5.48: Failure point of NXLN according to ESR test.

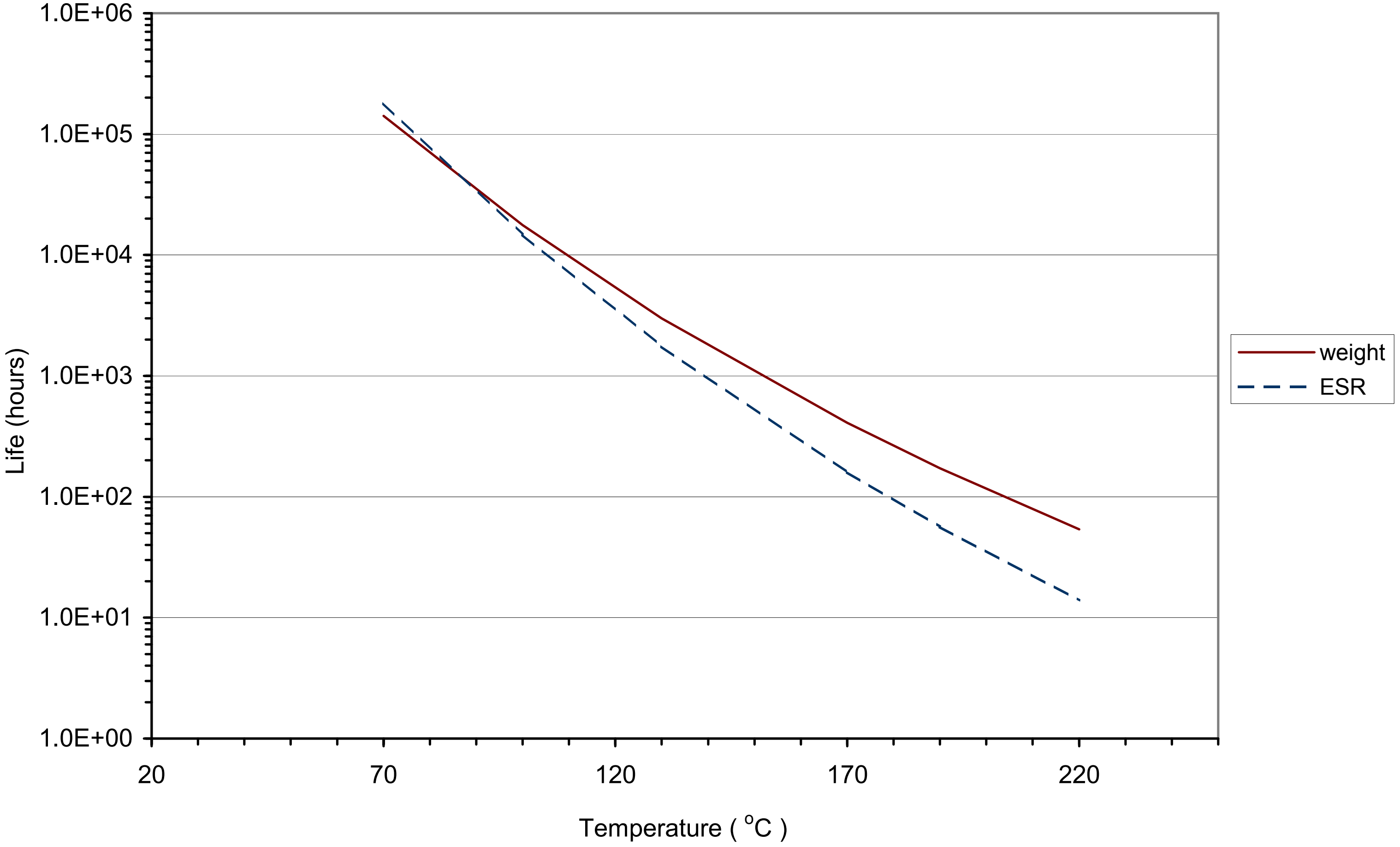


Figure 5.49: Thermal life-time of RXLN.

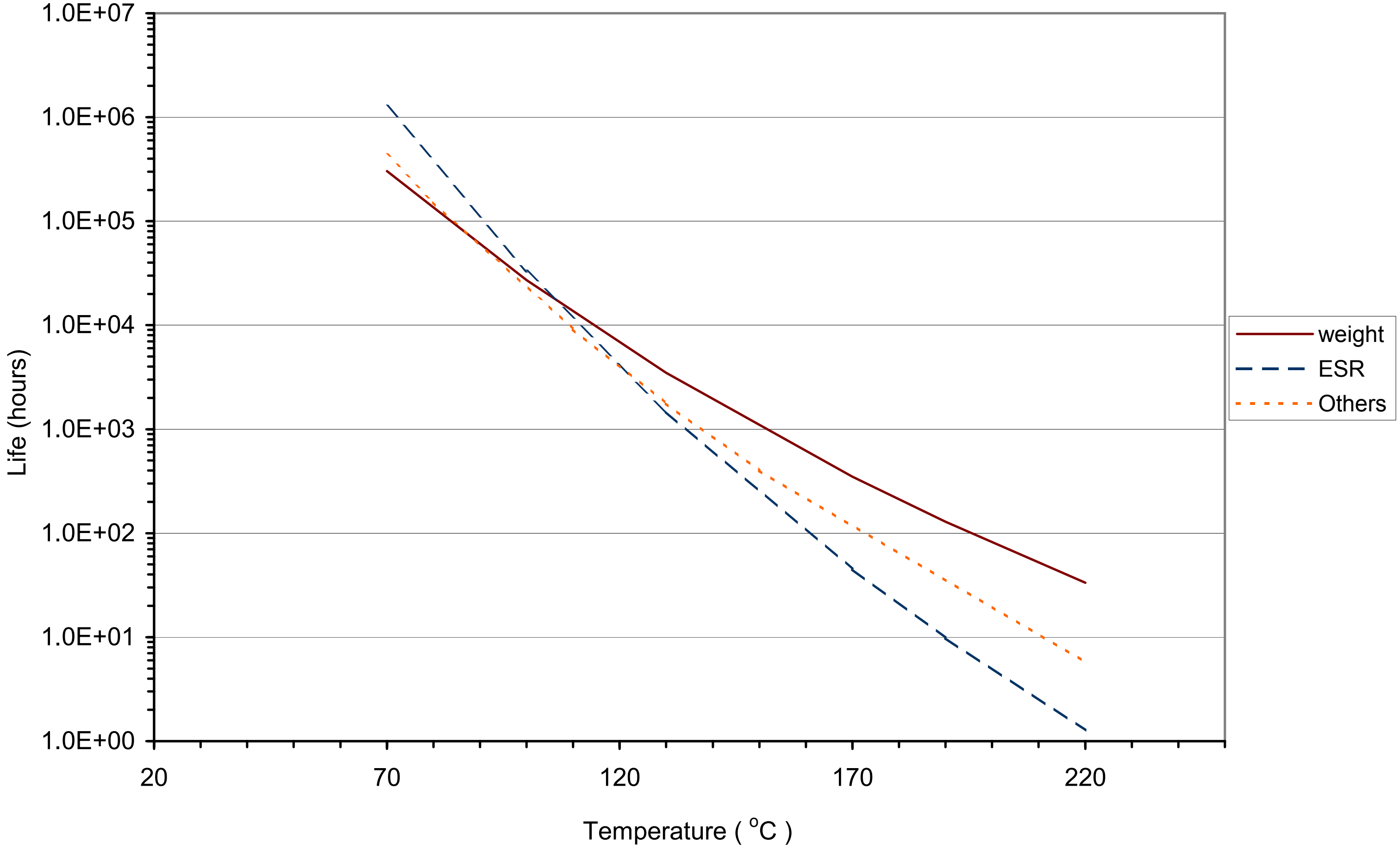


Figure 5.50: Thermal life-time of NXLN.

Figure 5.50 shows a lifetime plot of XLPE, which is a result of a research done on thermal endurance evaluation of XLPE insulation [78].

CHAPTER # 6

CONCLUSION AND RECOMENDATIONS

Because insulating materials deteriorated with heating over time, thermal history of cable insulations is essential to predict the cable life. Thermal history consists of two factors, which are the temperature and the exposure time. Cable insulations suffer various thermal stresses in its production process and in field such as, environmental conditions and applied load variations. [119]

Two methods have been used in this study to investigate the thermal of XLPE and PVC cable insulations. Conventional method called weight loss method is a measurement of the physical property of a material, and analytical method known as electron spin resonance (ESR) method. In weight loss method, selection of the end point influences determination of the thermal lifetime. The thermal stress results may be affected by the specimen size, especially the thickness, in which weight loss has shown a quite variable time behavior for some insulating materials [120].

The formation of radicals in the polymer chains due to degradation of the polymer is large enough to support partial discharge. This results from the dissociation and decomposition of the insulation. [122]

ESR studies have been performed in the past on irradiated polymers and many efforts have been devoted to the identification of radicals [121]. A singlet ESR spectrum, which is assigned to the polyenyl radical, is observed during thermal aging. This spectrum has not been observed before thermal aging. However, others said that free radicals have been observed easily in new cables [123].

The results show clear evidence that the thermal behavior of XLPE insulation is better than PVC insulation. Also, the results indicate that colorants enhance the thermal resistance of the PVC insulating material.

The results of weight loss test and ESR test are compared together. These results proof the powerfulness and importance of the ESR in such studies either alone or in combination with other methods.

The results of this experimental work show some important aspects to be taken into account in the manufacturing of cable insulations. These are:

1. The results indicate that colorants enhance the thermal behavior of PVC insulations. This means a caution should be taken in selecting the colorants used in PVC insulations.

2. The manufacturing process affects the thermal behavior. This means, the processing temperature of the insulation should be maintained to a lower range in order not to affect the manufactured insulation.

APPENDIX

Tow papers were published from this M.S. Thesis at the IEEE conference of Electrical Insulation and Dielectric Phenomena (CEIDP) held in New Mexico, USA, on October 2003. Copies of the papers are attached, and they are:

1. Novel exploration of cable insulation materials using electron spin resonance spectroscopy.
2. Thermal Aging Tests on XLPE and PVC Cable Insulation Materials of Saudi Arabia.

2003 Annual Report Conference on Electrical Insulation and Dielectric Phenomena

Novel exploration of cable insulation materials using electron spin resonance spectroscopy

M. A. Morsy[1], M. H. Shwehdi[2], A. M. Abu-Gurain[2]
[1]Chemistry Department, KFUPM, Saudi Arabia,
[2]Electrical Engineering Department, KFUPM, Saudi Arabia

Abstract: The electron spin resonance (ESR) study, as one of the best spectroscopic tools for direct spectral studies and analysis in material science, will be carried out to characterize and simulate the thermal stress and heat generated on insulation materials from practical loading of cable. The results will be used to evaluate the quality and main properties of raw and manufactured insulation materials. The presented work provides the first ESR investigation and evaluation of widely used power cable insulation materials, namely PVC and XLPE. The analysis will include locally manufactured and imported raw plastic materials used by some Saudi power cable factories. Additives, like colorant and/or stabilizer, are used to standard shades lines of cables for ready identification and to enhance their quality. It is also intended in this study to identify the effect of these additives on maintaining the insulation properties of the studied samples. The results of PVC or XLPE polymeric insulation materials can be extended from life tests to the application of these materials for higher quality and improvement cable materials.

Introduction

Polyethylene (PE) and polyvinyl chloride (PVC) are the principal materials used in the wire and cable industry. They provide insulation and jacketing for more than 30,000 different types of wire and cable products [1]. The easy processing and good insulation performance of PVC make it the polymer of choice in power cable construction. However, the recent technological improvement in insulation manufacturing trends toward using cross-linked polyethylene (XLPE) and other polymers that are more resistant to degradation from treeing, in addition to PVC, in high voltage cable construction [2-5].

During insulation manufacturing, plastics are exposed to heat that lead to degradation. The final product depends on the type of plastic, the additives used, and the processing temperature. Although degradation can not be eliminated completely, it must be held to a minimum to keep the quality of the final products high. However, the low thermal stability of PVC has been an area of intensive research, the relationship between microstructure and degradation behavior is still not fully understood.

The available methods for thermal endurance characterization of insulating materials are the conventional procedures and the analytical test methods [6]. The main advantage of the analytical test methods compared to the conventional methods is their ability to reduce test times without losing accuracy and practical significance of the results. Thermo-gravimetric analysis [7-9] and relaxation measurements [10] are two well known analytical methods. Electron spin resonance (ESR) method is another analytical method that has special potential in material degradation analysis, however, it is never used for the characterization of insulating materials used in cable industries.

This investigation will provide and conduct direct testing and investigation of thermal aging on widely used cable insulation materials (PVC and XLPE) to determine the endurance characteristics of raw and manufactured samples from major Saudi cable factories using ESR spectrophotometer for the first time. It is well known that ESR spectroscopy is the only technique established to detect radicals [11,12]. It has been used to detect and characterize free radicals from different sources [13]. Technological advancement made it feasible the comparative study between free radicals from the synthetic analogues such as rubber and plastic material. The results showed that free radicals from the synthetic analogues and plastics were 2-3 times higher than wood and wood - like material [14,15].

The study and analysis will be carried out to characterize and simulate the thermal stress to evaluate the quality and main properties of the insulation materials. The results of PVC and XLPE can be extended from life tests to the application of these materials for higher quality and improvement cable materials.

Practical Procedure and Methodology

Materials: Two main categories of each plastic type are used in this study; namely, raw and manufactured insulated materials. For example, raw PVC that is plastic received and will be used in cable insulation industry, while manufactured PVC insulation specimens are collected from new cables. Colorant effect on insulation material stability will be investigated by considering colored and non-colored samples as well.

0-7803-7910-1/03/$17.00 ©2003 IEEE

A number of sample sets have been prepared for the experiment. Five samples of PVC and XLPE insulations, as illustrated and coded in Table 1, are going to be studied.

Table 1: Insulating materials used in the experiment

Sample #	Insulating material type	Code
1	Raw* PVC non-color	RPVN
2	Raw* PVC red-color	RPVR
3	Manufactured** PVC red-color	MPVR
4	Raw* XLPE non-color	RXLN
5	Manufactured** XLPE non-color	MXLN

* Raw materials used in cable industry.

** Manufactured power cables insulation.

ESR Spectroscopy: It is used in many areas of physics, chemistry, and increasingly nowadays, biology and medicine to provide information on the structure of molecules and atomic particles in paramagnetic substances whether in the gas, liquid or solid states.

A basic spectrometer in the ESR consists of four freestanding main assembles, two sub-assemblies known as components, data acquiring unit and a microwave cavity. The main assemblies are a magnet, a magnet power supply unit, a microwave bridge and a console (spectrometer electronic and user interface). The components are a time base unit, a signal channel and a field controller: these are all mounted in the console, which incorporates power supply units and interconnections for these units. The cavity is supported between the poles of the magnet by a waveguide, which connects it to the microwave bridge. The general appearance of an ESR spectrometer from Bruker is shown in Fig. 1.

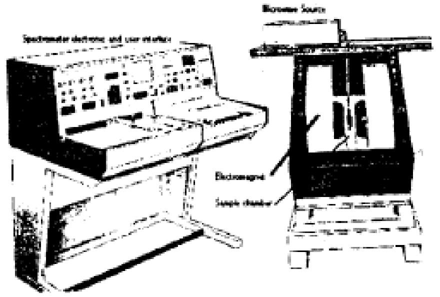


Figure 1: Bruker ER-300 ESR spectrometer.

The output of the instrument is in the form of a spectrograph covering a selected portion of the microwave region of the electromagnetic spectrum. The acquired data can be handled by different ESR software as well as MS-Excel programs. The spectrograph enables a skilled operator to analyze certain aspects of the chemical composition and molecular and atomic structures of the substances being tested.

One particular advantage of the resonance method is the negligible influence on the process being studied; it is non-destructive and non-perturbing. ESR spectroscopy can be used, therefore, with other forms of investigation on the same substance to obtain amore complete picture of the molecular structure and behavior.

Thermal aging unit: A well-design device to control thermal aging is used to age all the plastic samples under investigation. This device consists of a heater tape and pre-programmable controller. The controller supplies power to the heater and control the temperature inside a well-isolated container according to the pre-programmable condition. In addition, thermal sensors (Thermocouple) of the controller plus external thermometer were placed inside the sample holder to control and show the actual temperature of the heating environment for the aging process. The external thermometer will be used as reference to confirm the thermal stability as function of time.

Results and Discussion

PVC: Spectrographs of two PVC insulations, aged and non-aged, are presented in Fig. 2.

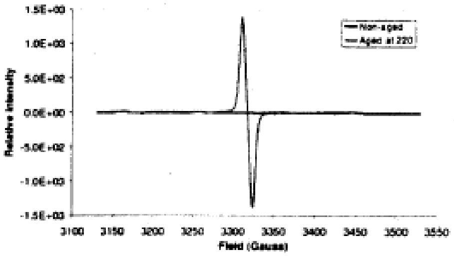
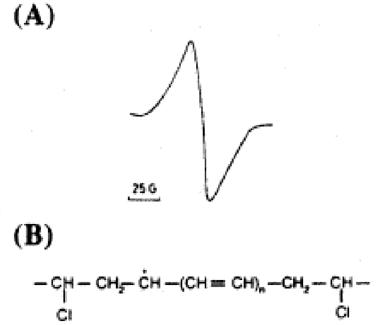


Figure 2: Samples of ESR spectrographs of raw PVC-red colored (RPVR) before and after aging at 220 °C for about 23.5 hours.

Cylindrical cavity has been used along with 9 GHz Microwave Bridge for all the investigated samples. The working parameters of the samples of the spectrometer are as follows: time constant = 655 ms, Mod. Freq. = 25 kHz, Mod. Amp. = 10 G, Freq. = 9.34 GHz, signal Gain = 10^4, sweep time = 120 s, and sample temperature = 22 °C. These instrumental factors were carefully selected to maximize signal intensity.

The observed pattern namely, singlet ESR-line, in Fig. 2 was observed during thermal [16-18], photo degradation [19,20], and chemical dehydrochlorination [21] of PVC. This singlet-line ESR-spectrum is assigned to a conjugated polyene structure of the macroradical (Fig. 3).



$$-\underset{\text{Cl}}{\underset{|}{\text{CH}}}-\text{CH}_2-\dot{\text{C}}\text{H}-(\text{CH}=\text{CH})_n-\text{CH}_2-\underset{\text{Cl}}{\underset{|}{\text{CH}}}-$$

Figure 3: ESR spectrum of γ-irradiated PVC-sample at room temperature in vacuum (A) and its molecular scheme (B).

The ESR-thermal aging results at 130 °C that is performed to investigate the effect of coloring of raw and its manufacturing process of PVC-insulation materials are shown in Fig. 4.

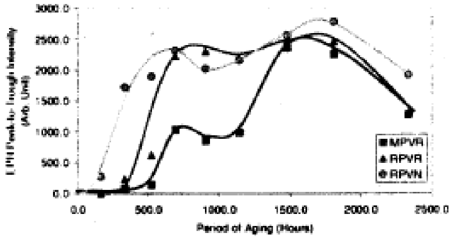


Figure 4: Accumulation of polyene radicals per sample (raw PVC-non-colored: RPVN, raw-PVC-red-colored: RPVR, or manufactured-PVC-red-colored; MPVR) during aging at 130 °C.

Results in Fig. 4 indicate that a similar behavior is observed from all the three samples except; (1) onset of degradation of the non-colored raw PVC (RPVN) and (2) intensity of the ESR-peak of the manufactured PVC (MPVR) within the first eight hundred hours of aging period. The earliest onset of the degradation of the non colored raw PVC can simply correlated with existence of the colorant. According to manufacturers of cables, pigments used in cable industry are carefully selected to enhance polymer stability that is also confirmed by our ESR-spectral results.

Regarding the intensity of the ESR-spectral signal, it has been observed that free radical formation at the first eight hundred aging hours from the raw materials is about 2.5 higher than that of the manufactured samples. On the other hand, the similar intensity of the different non-manufactured samples may correlate the difference in the intensities to the industrial processes of PVC insulation. The industrial process of PVC insulation of cable is expected to partially deform the original materials by removing amount of the good leaving HCl-molecules. The more the removal of the very corrosive HCl-system, the less polyene macroradicals is expected to be formed from the manufactured PVC insulation materials. The similarity in ESR-peak height of all the investigated samples after about 2000 hours of aging period at 130 °C (see Fig. 4) may be correlated with the similarity of aged material and certain our analysis.

XLPE: Spectrographs of two XLPE insulations, aged and non-aged, are presented in Fig. 5.

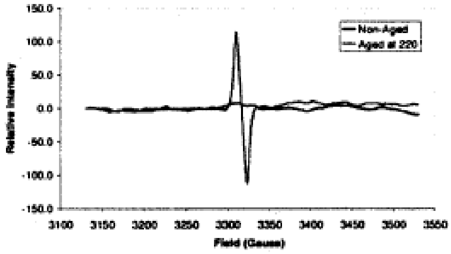


Figure 5: Samples of ESR spectrographs of raw XLPE-non colored (RXLN) before and after aging at 220 °C for about 23.5 hours.

The observed singlet ESR-Line in Fig. 5 is similar to the one reported in Fig. 2 and 3 of PVC-samples that is related to a conjugated polyene structure of the macroradical (Fig. 3). Similar spectrum was also observed when a polyethylene (PE) sample was γ-irradiated by doses of several thousands megarads [22-25]. The area under this singlet is again used to present the thermal aging effect similar to PVC-aged samples. Fig. 6 shows the aging effect on two XLPE samples at 130 °C.

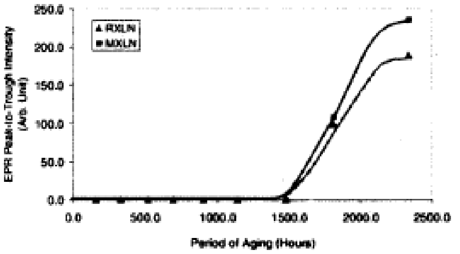


Figure 6: Accumulation of polyene radicals per sample (raw XLPE-non-colored; RXLN, or manufactured-XLPE-non-colored; MXLN) during aging at 130 °C.

The results in Fig. 6 indicate also that a similar behavior is observed from the two. The onset of the degradation of XLPE samples compared to PVC non-colored samples in Fig. 4 indicates that XLPE is ten to fifteen times better regarding their thermal degradation. This agrees with most of the other experimental results. Close examination of the results in Fig. 6 indicates that the manufacturing XLPE samples (MXLN) introduce more radicals than the non-manufactured one. This is in good agreement with the known properties of the XLPE, which is related to its molecular properties. By the way, it is also known that the XLPE cannot be recycled over the cable industry.

Conclusion

The thermal history of cable insulations is essential to predict the cable life. It consists of two factors; 1) temperature and 2) exposure time. Our ESR-spectral results add a third factor; molecular properties of the studied samples.

Thermal deterioration of the insulation materials over time is a well known property. The ESR-results show clear evidence that the thermal behavior of XLPE insulation is better than PVC insulation in good agreement with all the previous studies. The results also indicate that colorants clearly enhance the thermal resistance of the PVC insulating material. On the other hand, manufacturing process has a strong thermal effect on all the types of plastics. This experimental work shows the following important aspects to be taken into account in the manufacturing of cable insulations. First, a caution should be taken in selecting the colorants used in PVC insulations. Second, the processing temperature of insulation should be maintained to as lower as possible in order not to affect the final product of insulations.

Acknowledgment

This work has been supported by the Applied Research Income (ARI) and Jeddah Cables Company who supply the samples. The authors express their appreciation and gratitude to the financial support granted by the KFUPM, also, extend their appreciation to Jeddah Cables Company for their supply of samples and support.

References

[1] A Technical and Socio-Economic Comparison of Options to Products Derived from the Chlor-alkali Industry. CHEMinfo Services Inc., Canada, 1997.

[2] Fukudu, T.; Iwata, Z.; Irie: S.; Matsuki, M.; Kujiki, S.; Takayama, Y. and Ishihara, K., "Progress in Technology for High-Voltage Power Cables Insulated with Crosslinked Polyethylene." Furukawa Review, no. 5, 1987, pp. 1-18.

[3] Kobayashi, Kazuharu; Nakayama, Shiroh and Niwa, Toshio, " A New Estimation Method of Thermal History in Crosslinked Polyethylene" Proceedings of the 4^{th} International Conference on Properties and Applications of Dielectric Materials, July 3-8, 1994, pp. 678-81.

[4] Kujirai, T. and Akagira, T., "Effect of Temperature on the Deterioration of Fibrous Insulation Materials." Sci. Papers Inst. Phys. Chem. Res., Vol. 2, 1925, pp. 223-252.

[5] Mazzanti, G.; Montanari, G. C. and Simoni, L., "Conditions by Accelerated Life Tests: An Application to XLPE and EPR for High Voltage Cables." IEEE Electrical Insulation Magazine, Vol. 13, no. 6, Dec 1997, pp. 24-34.

[6] Montanari, G.C. and Motori, A., "Thermal Endurance Evaluation of XLPE Insulated Cables." J. Phys. D: Appl. Phys., 24, 1991, pp. 1172-81.

[7] Toop, D.J., "Theory of Life Testing and Use of Thermogravimetric Analysis to Predict the Thermal Life of Wire Enamels." IEEE Transactions on Electrical Insulation, Vol. 6, 1971, pp. 2-13.

[8] Yi, B.; Yingsuo, Z. and Youxiu, M., 1^{st} IEEE ICPADM, 1985, pp. 218-20.

[9] Chinese Standard JB1544, 1988.

[10] Crine, J.P., "Rate Theory and Polyethylene Relaxations." IEEE Transactions on Electrical Insulation, Vol. 22, 1987, pp. 169-74.

[11] Zavoisky, E., J. Phys. U.S.S.R., 9:211, 245, 1945.

[12] Atherton, N. M. Principles of Electron Paramagnetic Resonance: Ellis Horwood: London, 1993.

[13] Batchelor, S. N.; Henningsen, B. and Fisher, H., J. Phys. Chem., 101, 2969, 1997.

[14] Pryor, W. A.; Hales, B. J.; Premovic, P.I. and Chruch, D. F., "The Radicals in Cigarette Tar: Their Nature and Suggested Physicological Implications" Science, Vol. 220, 1983, pp. 425-27.

[15] Kuzina, S. I.; Pivovarov, A. P.; Belov, G. P. and Mikhailov, A. I., High Energy Chemistry, 31, 382, 1997.

[16] Hay, J. N.: J. Polym. Sci. A1, 8, 1201 (1970).

[17] Liebman, S. A., Ahlstrom, D. A., Quinn, E. J., Geigley, A. G., Meluskey, J. T.: J. Polym. Sci. A1, 9, 1921 (1971).

[18] Liebman, S. A., Reuwer, J. F., Gollatz, K. A., Nauman, C. D.: J. Polym. Sci. A1, 9, 1823(1971).

[19] Tsuchida, E. Shin, C. N., Shinohara, I., Kambara, S.: J. Polym. Sci. A1, 2, 3347 (1964).

[20] Tsuji, K.: Adv. Polym Sci. 12, 131 (1973).

[21] Wen, W. Y., Johnson, D. R., Dole, M.: J. Phys. Chem. *78*, 1798 (1974).

[22] Lawton, E. J., Balwit, J. S., Powell, R. S.: J. Chem. Phys. *33*, 405 (1960).

[23] Ohnishi, S., Ikeda, Y., Sugimoto, S., Nitta, I.: J. Polym. Sci. *47*, 503 (1960).

[24] Ohnishi, S., Sugimoto, S., Nitta, I.: J. Polym. Sci. *A1*, *1*, 605 (1963).

[25] Ohnishi, S., Sugimoto, S., Nitta, I.: J. Chem. Phys. *39*, 2647 (1963).

2003 Annual Report Conference on Electrical Insulation and Dielectric Phenomena

Thermal Aging Tests on XLPE and PVC Cable Insulation Materials of Saudi Arabia

M. H. Shwehdi[1], M. A. Morsy[2], A. Abugurain[1]
Electrical Engineering Department[1], Chemistry Department[2], King Fahd University of Petroleum & Minerals,
Dhahran, Saudi Arabia

Abstract: Saudi Arabia has four cables manufacturers, and one raw polymer material producer. XLPE and PVC are the most widely used materials in cable insulation industries. The sever weather environment of the Kingdom adds tremendous factors in stressing these cable insulations and shortens their lifetime.

The study presents preliminary results of a comprehensive thermal aging investigation on medium and high voltage cable insulation materials using different analytical techniques; especially weight loss method, to determine how "good" and "safe" are the insulation materials used in cables manufacturing. Since weight loss is a significant physical property that considered to be influenced by thermal degradation, this method is used as a diagnostic procedure to detect the degree of aging.

Introduction

Power transmission cables generally consist of a metal conductor surrounded by multiple insulation layers. For protection against mechanical damage and water contact, jacketing is extruded around one or more of the insulated conductor wires. Polyethylene (PE) and polyvinylchloride PVC are the principal materials used in the wire and cable industry. They provide insulation and jacketing for more than 30,000 different types of wire and cable products [1].

The easy processing and good insulation performance of polyvinyl chloride (PVC) make it the polymer of choice in power cable construction. However, the recent technological improvement in insulation manufacturing trends toward using cross-linked polyethylene (XLPE) and other polymers that are more resistant to degradation from treeing, in addition to PVC, in EHV cable construction [2, 5]. Much of these insulating materials are colored to standard shades for ready identification. The colorants must be carefully chosen to maintain the insulation properties of the polymer. Although the low thermal stability of PVC has been an area of intensive research, the relationship between microstructure and degradation behavior is still not fully understood.

During insulation manufacturing, plastics are exposed to heat that lead to degradation. The final product depends on the type of plastic, the additives used, and the processing temperature. Although degradation can not be eliminated completely, it must be held to a minimum to keep the quality of the final products high.

Thermal degradation of polyvinyl chloride (PVC) and cross-linked polyethylene (XLPE) raw and cable-manufactured materials are experimentally investigated using weight loss method to simulate the thermal stress to evaluate the quality and main properties of the insulation materials. Effect of the standard color used in cables and thermal treatment over the cable insulation process is also correlated.

These investigations and experimental results also should yield a better understanding of the different thermal effects in the industrial processes of the insulation materials used in cable fabrication in Saudi Arabia.

Insulations of electric power cables are stressed by severe weather environment of the kingdom of Saudi Arabia, that adds tremendous factors in stressing cable insulations and shortens their lifetime. The petrochemical industries in Saudi Arabia are striving to improve the quality of the polymers raw materials used in cable insulation industries.

PVC can be compounded to retain its performance properties over a broad temperature range. Most PVC is rated for safe use at 90°C and 75°C in wet conditions, but some can be used safely up to 105°C. Most XLPE is rated for 90°C in both wet and dry conditions. XLPE generally has higher tensile strength with higher resistance to abrasion and weathering. Development work continues to increase the maximum temperature rating of both compounds to 105°C, in order to increase the capacity to carry current. Thermoplastic PE will not operate satisfactorily at temperatures of 90°C, since it softens and melts near this temperature. Above about 107°C, XLPE softens somewhat, but is still more resistant to deformation than PVC, and continues to provide good insulation at temperatures up to about 150°C. [1]

As thermoplastics, the processing of PVC, thermoplastic PE and TPE wire and cable is a relatively straightforward extrusion process. In contrast, the processing of XLPE is a reactive system, which can require special handling of multiple raw material components, unique product curing technologies and increased process control requirements.

0-7803-7910-1/03/$17.00

The manufacturing of coated wire and cable is a multi-stage process. Raw materials are combined in a series of manufacturing steps including resin and additive manufacturing; resin compounding, wire drawing, extrusion, cabling, and jacketing. All polymers undergo degradation and decomposition when exposed to heat during formulation or molding into products. They also tend to break down when subject to the mechanical stress of molding or extrusion.

Colorants are added to wire and cable resins for identification purposes. There are two major types of colorants pigments and dyes. A pigment is insoluble and is dispersed as discrete particles throughout a resin to achieve a color. Pigments can be either organic or inorganic compounds. A dye is soluble in the resin and always an organic based material.

PE and XLPE have better insulating properties than PVC and are used in more applications. In the middle to late 1950s, cross-linkable polyethylene compounds were introduced for coating power cable [8]. The unusual and excellent electrical properties of polyethylene are extended to higher operating temperatures when used in cross-linkable materials.

The most important advantage of cross-linked polyethylene (XLPE) over thermoplastic polyethylene is the improved heat resistance. An XLPE insulated power cable can operate at conductor temperatures of 90°C, while the thermoplastic polyethylene insulated cable operates at 75°C. Since conductor temperature is proportional to the amount of loading current through the cable, more power can be transmitted through an XLPE cable than through a non-cross-linked cable of the same size.

After 1950, as the materials were diversified and the electrical appliances were made smaller and better in performance through the development of the molecular industry, the importance of the thermal endurance test was recognized and the number of reports concerning thermal aging and thermal endurance of various materials increased. [4]

Thermal Aging

The main stress for insulating materials is the electrical one, because voltage is always applied to them. However, insulation is usually exposed to multi-stress conditions: such as, high temperatures, pollution, humidity, radiations, vibrations and so on. Even when other stresses have a much greater effect than the electrical gradient, failure is still due to electrical breakdown. This occurs when electric strength, because of aging, decays to the value of the applied electrical gradient. Decline of electric strength is due to all the stresses acting on the material which are the cause of its aging. [7]

Life tests are normally carried out to assess endurance of insulating materials. They consist of exposing specimens of the insulating material to constant stress until they fail. The time to failure in operating conditions should be predicted from a statistical point of view from these tests. Since this result must be obtained in times much shorter than the expected life in service, the tests are performed in heavier conditions than the operating ones. [7]

Electrical insulation, organic materials in particular, exposed to elevated temperatures are subject to deterioration. Deterioration produces changes in the physical properties of materials so that they become unable to meet their functions after a certain time.

Therefore, thermal stress can produce failure without destroying the specimen, and for this reason the limiting value is established according to a criterion, which must take into account the function that the material is expected to meet in service. Since the rate of deterioration increases rapidly with rising temperature, which causes an acceleration of the chemical reactions occurring in materials, therefore, it is necessary to limit the temperature to ensure long life of electrical equipment. Because thermal behavior of materials considerably changes from one material to another, insulating materials have been classified according to the maximum temperature they are able to endure for a satisfactorily long period of time. [7]

Since thermal deterioration is due to the acceleration of chemical reactions produced by increasing temperature, the aging rate can be assumed proportional to the rate of chemical reactions. Therefore, the aging rate dependent on temperature according to the following relationship known as the Arrhenius law:

$$R = R' \exp\left(-\frac{W}{KT}\right) \qquad (1)$$

Where W is the activation energy, K Boltzman's constant and T the absolute temperature ($T = 273 + \theta$). The material life, that is the time to reach the failure criterion, is:

$$L = L' \exp(B/T) \qquad (2)$$

Where $B = W / K$ and L' is a constant for the material under consideration that equals the life of material when temperature tends to infinity.

According to (2), L becomes infinite only at absolute zero temperature, because only at that temperature the chemical reactions are ceased. However, if a material is kept at room temperature without any stress applied, its life is practically infinite. Therefore, life at room temperature, L_o, is introduced instead of L'. Therefore:

$$L = L \exp\left(\frac{B}{T_o}\right) \tag{3}$$

Where, T_O is the absolute room temperature, it follows that:

$$L = L_o \exp(-B \quad cT) \tag{4}$$

Where,

$$cT = \frac{1}{T_o} - \frac{1}{T} = \frac{T - T_o}{TT_o} \tag{5}$$

is the conventional thermal stress.

Since cables are mainly subjected in service to electrical, thermal and mechanical stresses, the properties measured in the aging tests are electric strength, weight, tensile strength and modulus. The selected property for thermal aging evaluation is the weight. IEC Standard 216 establishes recommended end points and properties to obtain thermal endurance line for each studied material. A decrease of electric strength to 50 % of its initial value provides thermal endurance line close to those obtained by 50 % drop in tensile modulus and a 0.5 % decrease of weight [6]. The test temperatures are 220, 170 and 130 °C.

PVC and XLPE insulations are the major insulating materials used in cable insulation industries. Different samples of these insulation materials are tested in this experiment.

Two main categories of PVC and XLPE are used in this study; namely, raw and manufactured insulated materials. For example, raw PVC is the plastic used in cable insulation, while manufactured PVC insulation specimens are collected from new cables. Colorant effect on insulation material stability will be investigated by considering colored and non-colored samples as well.

A number of sample sets have been prepared for the experiment. Each set includes seven samples of PVC and XLPE insulations as illustrated and coded in table 1.

Table 1: Insulating materials used in the experiment

Sample #	Insulating material type	Code
1	Raw* PVC non-color	RPVN
2	Raw* PVC black-color	RPVB
3	Raw* PVC red-color	RPVR
4	New** PVC red-color	NPVR
5	New** PVC black-color	NPVB
6	Raw* XLPE non-color	RXLN
7	New** XLPE non-color	NXLN

* Raw materials used in cable industry.

** Manufactured power cables insulation.

PVC Results

The results of weight property of two PVC insulations at different testing temperatures are plotted against time in figures 1 and 2. The code used in table 1 will be used here to identify the samples. From these results the thermal life-lines of the tested PVC insulations are obtained.

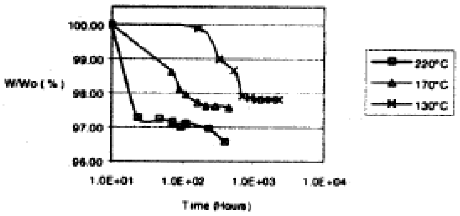


Figure 1: Weight property against aging time for RPVB.

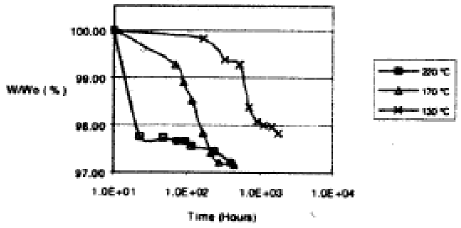


Figure 2: Weight property against aging time for NPVB.

The effect of temperature can be noted very clearly from the results of the weight loss test. The thermal life-lines in figure 3 indicate that the life of the insulating material is inversely related with the temperature. The life of the insulation shortens as the temperature increases.

Figure 4 shows the thermal life-lines of different colored raw PVC samples. There is a slight difference between the three lines, which indicates higher endurance of RPVR in low temperatures up to the operating range (105 °C) followed by RPVB. This means that colorants enhance the thermal resistance of PVC insulations.

The effect of manufacturing process on PVC insulating materials is shown in figure 5. The black-colored manufactured PVC insulation has better thermal resistance than the raw black-colored PVC above 100°C.

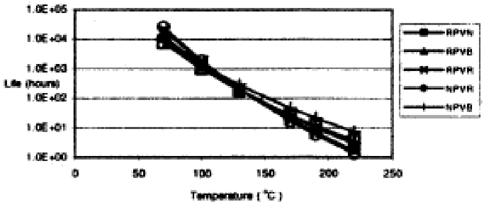


Figure 3: Thermal life-lines of PVC insulations based on weight property results.

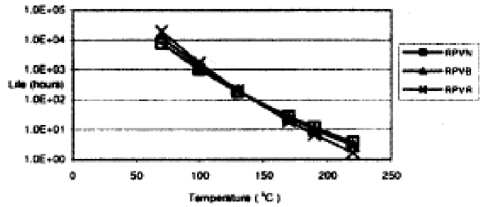


Figure 4: Thermal life-lines of raw PVC insulations based on weight property results.

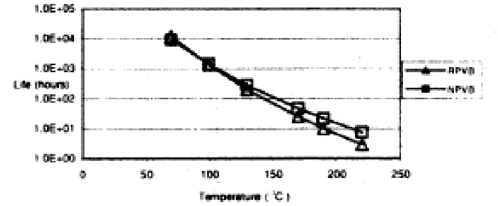


Figure 5: Thermal life-lines of black-colored PVC insulations based on weight property results.

XLPE Results

Weight property results of XLPE samples are shown in figures 6 and 7. The thermal life-lines of XLPE are obtained from the results of weight property.

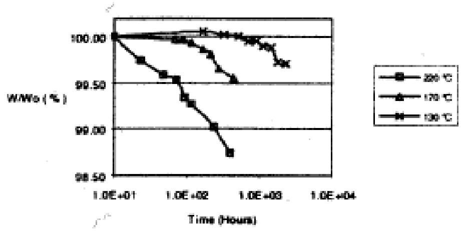


Figure 6: Weight property against aging time for RXLN.

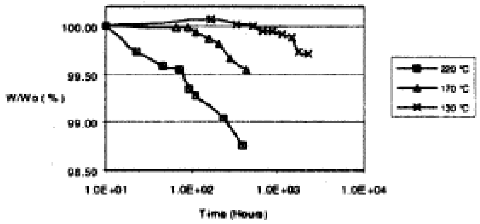


Figure 7: Weight property against aging time for NXLN.

The thermal life-lines of XLPE insulations are plotted in figure 8. The life of XLPE insulations is shortened as the temperature increases. Also, figure 8 shows the effect of the manufacturing process on XLPE insulation. The raw XLPE insulation is better than the manufactured XLPE. The manufacturing process decreases the thermal endurance of XLPE insulation.

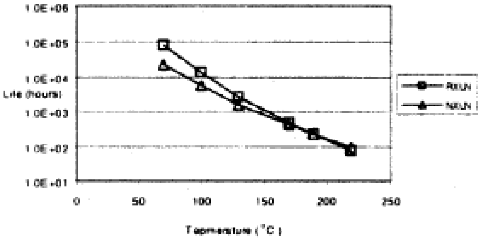


Figure 8: Thermal life-lines of XLPE insulations based on weight property results.

Comparison Between PVC and XLPE

The thermal life-lines of XLPE and PVC insulations are illustrated in figure 9 based on weight property results. It is clear that XLPE is more endurable than PVC. For example, at 100 °C XLPE lifetime is more than 10,000 hours, while PVC lifetime is around 1,000 hours. However, both XLPE and PVC insulations exhibit low thermal endurance at high temperatures.

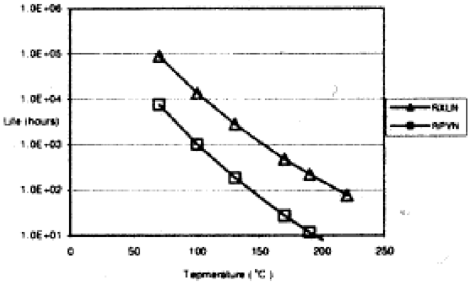


Figure 9: Thermal life-lines of PVC and XLPE insulations based on weight property.

Conclusion

Because insulating materials deteriorate with heating over time, thermal history of cable insulations is essential to predict the cable life. Thermal history consists of two factors, which are the temperature and the exposure time. Cable insulations suffer various thermal stresses in its production process and in field such as, environmental conditions and applied load variations.

The results show clear evidence that the thermal behavior of XLPE insulation is better than PVC insulation. The manufacturing process improves the thermal behavior of PVC while it affects that of XLPE. Also, the results indicate that colorants enhance the thermal resistance of the PVC insulating material.

The results of this experimental work show the following important aspects to be taken into account in the manufacturing of cable insulations. First, a caution should be taken in selecting the colorants used in PVC insulations.

Second, the manufacturing process affects the XLPE thermal behavior, while it improves the PVC insulation. This means, the processing temperature of XLPE insulation should be maintained to a lower range in order not to affect the final product of XLPE insulation. Some recommendations are to be supplied to Jeddah Cables Company whose insulating materials samples are tested.

Acknowledgment

The authors express their appreciation and gratitude to the financial support granted by the KFUPM, also, extend their appreciation to Jeddah Cables Company for thire supply of samnples and support.

References

[1] A Technical and Socio-Economic Comparison of Options to Products Derived from the Chlor-alkali Industry, CHEMinfo Services Inc., Canada, 1997.

[2] Fukudu, T.; Iwata, Z.; Irie: S.; Matsuki, M.; Kujiki, S.; Takayama, Y. and Ishihara, K., "Progress in Technology for High-Voltage Power Cables Insulated with Crosslinked Polyethylene." Furukawa Review, no. 5, 1987, pp. 1-18.

[3] Kobayashi, Kazuharu; Nakayama, Shiroh and Niwa, Toshio, " A New Estimation Method of Thermal History in Crosslinked Polyethylene" Proceedings of the 4th International Conference on Properties and Applications of Dielecric Materials, July 3-8, 1994, pp. 678-81.

[4] Kujirai, T. and Akagira, T., "Effect of Temperature on the Deterioration of Fibrous Insulation Materials." Sci. Papers Inst. Phys. Chem. Res., Vol. 2, 1925, pp. 223-252.

[5] Mazzanti, G.; Montanari, G. C. and Simoni, L., "Conditions by Accelerated Life Tests: An Application to XLPE and EPR for High Voltage Cables." IEEE Electrical Insulation Magazine, Vol. 13, no. 6, Dec 1997, pp. 24-34.

[6] Montanari, G.C. and Motori, A., "Thermal Endurance Evaluation of XLPE Insulated Cables." J. Phys. D: Appl. Phys., 24, 1991, pp. 1172-81.

[7] Simoni: Luciano, Fundamentals of Endurance of Electrical Insulating Materials, Editrice Clube Bologona, Italia, 1983.

[8] The Chemistry of Polyethylene Insulation, Equistar.

CHAPTER # 7

REFERENCES

1. Fukudu, T.; Iwata, Z.; Irie; S.; Matsuki, M.; Kujiki, S.; Takayama, Y. and Ishihara, K., “Progress in Technology for High-Voltage Power Cables Insulated with Crosslinked Polyethylene.” Furukawa Review, no. 5, 1987, pp. 1-18.

2. Mazzanti, G.; Montanari, G. C. and Simoni, L., “Conditions by Accelerated Life Tests: An Application to XLPE and EPR for High Voltage Cables.” IEEE Electrical Insulation Magazine, Vol. 13, no. 6, Dec 1997, pp. 24-34.

3. Flicker, T. M.; and Green, S. A., “Detection and Separation of Gas-Phase Carbon-Centered Radicals from Cigarette Smoke and Diesel Exhaust” Anal. Chem., Vol. 70, 1998, pp. 2008-2012.

4. Church, D., Anal. Chem., 66, 419A, 1994.

5. Tanaka, J., “Insulation Aging Studies By Chemical Characterization.” IEEE Transactions on Electrical Insulation, Vol. EI-15, 1980, pp. 201-5.

6. Nitta, Yoshitaka; Fukagawa, Hiromasa and Takashima, Hideaki, “Breakdown Voltage of XLPE Cables Pre-Heated by Excess Current.” IEEE Transactions on Electrical Insulations, Vol. EI-13, No. 1, Feb 1978, pp. 62-4.

7. IEC-Standard 216: Guide for the determination of Thermal Endurance Properties of Electrical Insulating Materials; Bureau Central de la CEI, Geneve, Suisse.

8. Zavoisky, E., J. Phys. U.S.S.R., 9:211, 245, 1945.

9. Atherton, N. M. Principles of Electron Paramagnetic Resonance; Ellis Horwood: London, 1993.

10. Batchelor, S. N.; Henningsen, B. and Fisher, H., J. Phys. Chem., 101, 2969, 1997.

11. Pryor, W. A.; Hales, B. J.; Premovic, P.I. and Chruch, D. F., “The Radicals in Cigarette Tar: Their Nature and Suggested Physicological Implications” Science, Vol. 220, 1983, pp. 425-27.

12. Kuzina, S. I.; Pivovarov, A. P.; Belov, G. P. and Mikhailov, A. I., High Energy Chemistry, 31, 382, 1997.

13. Brancato, E. L., “Insulation Aging A Historical and Critical Review” IEEE Transactions on Electrical Insulations, Vol. EI-13, No. 4, August 1978, pp. 308-17.

14. A Technical and Socio-Economic Comparison of Options to Products Derived from the Chlor-alkali Industry, CHEMinfo Services Inc., Canada, 1997.

15. Power Cable Manual, South Wire Company, USA, 1999.

16. The Chemistry of Polyethylene Insulation, Equistar.

17. Insulation and Jacket Materials, Technical Guide, Industrial Electric Wire and Cable Inc.

18. General Guide to Plastics, West Coast Lockwasher, California, USA, www.wclco.com.

19. "Research Needs to Assess the Long-Term Performance of Electrical Insulating Materials and Systems." The National Res. Council Conf. on Electrical Insulation and Dielectric Phenomena, Commission on Sociotechnical Systems, 1977.

20. http://www.jeddah-cable.com.

21. http://www.xenel.com/site/text_only/industrial.htm.

22. http://www.riyadh-cables.com.

23. Ieda, M.; Sawa, G. and Nagao, M., "On the Temperature Dependence of Electric Strength of Polyethylene." Internationales Symposium Hochspannungstechnik, Zurich, 5.1-04, 1975, pp. 587-91.

24. Austen, A. E. W. and Pelzer, H., "The Electric Strength of Paraffins and Some High Polymers." J. Inst. Elect. Engrs., Vol. 93(I), 1946, pp. 525-532.

25. McKeovm, J. J., "Intrinsic Electric Strength of Organic Polymeric Materials." Proc. Inst. Elect. Engrs., Vol. 112, 1965, pp. 824-828.

26. Fischer, P. H. H. and Nissen, K. W., "The Short-Time Electric Breakdown Behavior of Polyethylene." IEEE Trans., Vol. EI-11, 1976, pp. 37-40.

27. Watson, D. W., "Dielectric Breakdown of Perspex Electrets in Nonuniform Fields." IEEE Trans., Vol. EI-8, 1973, pp. 6-9.

28. Ball, I. D. E., "The Intrinsic Electric Strength of Polyvinyl Alcohol and Its Temperature Variation." Proc. Inst. Elect. Engrs., Vol. 98(I), 1951, pp. 84-6.

29. Oakes, W. G., "The Intrinsic Electric Strength of Polythene and Its Variation with Temperature." J. Inst. Elect. Engrs., Vol. 95(1), 1948, pp. 36-44.

30. Oakes, W. G., "The Electric Strength of Some Synthetic Polymers." J. Inst. Elect. Engrs., Vol. 96(1), 1949, pp. 37-43.

31. Artbauer, J. and Griac, J., "The Intrinsic Electric Strength of Polymers and Its Relation to the Structure Part I: Experimental." Acta Technica CSAV, No. 3, 1966, pp. 416-28.

32. Amakawa, K.; Moriuchi, T.; Yoshida, T. and Inuishi, Y., "Electric Conduction and Dielectric Breakdown of Polyethylene Films." J. Inst. Elect. Engrs. Of Japan, Vol. 84, 1964, pp. 129-35.

33. Wargner, K. W., "The Physical Nature of the Electrical Breakdown of Solid Dielectrics." AIEE Trans., Vol. 41, 1922, pp. 288-99.

34. Rogowski, W., "Der elektrische Durchschlag von Gasen, festen und flussigen Isolatoren." Arch. Elektrotech., Vol. 19, 1930, pp. 569-78.

35. Hippel, A. von, "Electric Breakdown of Solid and Liquid Insulators." J. Appl. Phys., Vol. 8, 1937, pp. 815-32.

36. Whitehead, S., "Dielectric Breakdown of Solids." Clarendon Press, Oxford, 1953.

37. O'Dwyer, J. J., "The Theory of Electrical Conduction and Breakdown in

Solid Dielectrics." Clarendon Press, Oxford, 1973.

38. Inuishi, Y.; Onishi, K.; Tada, Y. and Suita, N., "Secondary Factors in Dielectric Breakdown of Solids." J. Inst. Elect. Engrs. of Japan, Vol. 76, 1956, pp. 913-8.

    Artbauer, J. and Griac, J., "Intrinsic Electric Strength of Polythene in the High-Temperature Region." Proc. Inst. Elect. Engrs., Vol. 112, 1965, p. 818.

39. Frohlich, H., "On the Theory of Dielectric Breakdown in Solids." Proc. Roy. Soc., Vol. A-13S, 1947, pp. 521-32.

40. Stark, K. H. and Carton, C. G., "Electric Strength of Irradiated Polythene." Nature, Vol. 176, 1955, pp. 1225-6.

41. Artbauer, J., "Elektrische Festigkeit von Polymeren." Kolloid Z. und Z. Polymere, Vol. 202, 1965, pp. 15-25.

42. Augood, D. P., "Dielectric Aging - Overview and Comment." Proceedings of 1978 IEEE International Symposium on EI, 1978, pp. 17-21.

43. Simoni, L., "A General Approach to the Endurance of Electrical Insulation Under Temperature and Voltage." IEEE Transactions on EI, Vol. 16, 1981, pp. 278-89.

44. Montanari, G. C.; Pattini, G. and Simoni, L., "Investigation on the Combined-stress Behavior of XLPE Insulated Cables." Proceedings of 1985 IEEE International Conference on Properties and Applications of Dielectric Materials, 1985, pp. 709-12.

45. Simoni, L.; Mazzanti, G. and Montanari, G. C., "Life Models for Insulating Materials in Combined-stress Conditions." Proceedings of 1994 ICPADM Conference, 1994, pp. 827-32.

46. Carton, A.; Bamji, S.; Bulinski, A. and Densley, J., "Oxidation and Water Tree Formation in Service-aged XLPE Insulation." IEEE Transactions on EI, Vol. 22,1987, pp. 405-12.

47. Parasie, Y.; Pinet, A. and Roy, D., "The Effect of Water on the Dielectric Performance of a Cable." Revue Generale de l'Electricite, Vol. 3,1984, pp. 151-6.

48. Bahder, G.; Garrity, T.; Sosnowski, M.; Eaton, R. and Katz, C., “Physical Model of Electric Aging and Breakdown of Extruded Polymeric Insulated Power Cables." IEEE Transactions on PAS, Vol. 101, 1982, pp. 1378-88.

49. Kiersztyn, S. E., "Formal Theoretical Foundation of Electrical Aging of Dielectrics." IEEE Transactions on PAS, Vol. 100, 1981, pp. 4330-40.

50. Hirose, H., "A Method to Estimate the Lifetime of Electrical Insulation." IEEE Transactions on EI, Vol. 22, 1987, pp. 745-53.

51. Tanaka, T. and Greenwood, A., Advanced Power Cable Technology, Vol. I, CRC Press, 1983, pp. 117-30.

52. Starr, W. T. and Endicott, H. S., "Progressive Stress - A New Accelerated Approach to Voltage Endurance." AIEE Transactions on PAS, Vol. 80, 1961, pp. 515-23.

53. McKean, A. L.; Tsuji, D.; Doepken, M. C. and Zidon, A., "Breakdown Mechanism Studies in XLPE Cable." IEEE Transactions on PAS, Vol. 97, 1978, pp. 1167-75.

54. Dakin, T. W., "Electrical Insulation Deterioration Treated as a Chemical Rate Phenomenon." AIEE Transactions, Vol. 67, 1948, pp. 113-122.

55. Dakin, T. W., "Electrical Insulation Deterioration." Electrotechnology, Vol. 3, 1960, pp. 129-130.

56. Dakin, T. W. and Studniarz, S. A., "The Voltage Endurance of Cast Epoxy Resins." 1978 IEEE International Symposium on EI, 1978, pp. 216-21.

57. Starr, W. T. and Steffens, H. G., "Searching for Thresholds in Voltage Endurance." 1985 International Conference on Properties and Applications of Dielectric Materials, 1985, pp. 285-94.

58. Hibma, T. and Zeller, H. R., "Direct Measurement of Space Charge Injection from a Needle Electrode into a Dielectric." Journal of Applied Physics, Vol. 59, 1986, pp. 1614-20.

59. Mazzanti, G.; Montanari, G. C. and Simoni, L., "Multistress Endurance Characterization of Epr Cable Models." 1994 IEEE International Symposium on EI, 1994, pp. 264-8.

60. Endicott, H. S.; Hatch, B. D. and Sohmer, R. G., "Applications of the Eyring Model to Capacitor Aging Data." IEEE Transactions on Component Parts, Vol. 12, 1965, pp. 34-41.

61. Crine, J. P. and Vijh, A. K., “A Molecular Approach to the Physico-chemical Factors in The Electric Breakdown of Polymers.” Applied Physics Communications, Vol. 5, 1985, pp. 139-63.

62. Crine, J. P.; Parpal, J. L. and Dang, C., ‘A New Approach to the Electric Aging of Dielectrics.” Proceedings of 1989 Conference on Elctrical Insulation and Dielectric Phenomena, 1989, pp. 161-7.

63. Montanari, G. C. and Mazzanti, G., "From Thermodynamic to Phenomenological Multi-stress Models for Insulating Materials without or with Evidence of Threshold." J. Physics D, Vol. 27, 1994, pp. 1691-702.

64. Boulter, A., "Mechanical Stresses as Ageing Factors of Electrical Insulation Systems." International Electrotechnical Commission Technical Committee No. 63: Insulation Systems (DRAFT), June 1976.

65. Paloniemi, P., "Isothermal Differential Calorimetry as a Means to Measure Insulation Aging Rate Down to the Operating Temperatures." IEEE Transactions on EI, Vol. 7, 126 (1972).

66. Kelen, A., "Short Time Ageing Tests." NORDIC Insulation Symposium, 1974.

67. Kujirai, T. and Akagira, T., “Effect of Temperature on the Deterioration of Fibrous Insulation Materials.” Sci. Papers Inst. Phys. Chem. Res., Vol. 2, 1925, pp. 223-252.

68. Akahira, T., “Table No.3.” Sci. Papers Inst. Phys. Chem. Res., 1928, pp. 181-215.

69. Committee on Deterioration for Organic Material.” Thermal Rating of Electrical Insulating Materials.” Technical Report of IEEJ, No. 19, 1957, pp. 12-20.

70. Ozawa, T., “A Method of Analyzing Thermogravmetric Data.” Bull. Chem. Soc. Japan, Vol. 38, 1965, pp. 1881-1886.

71. Takahashi, Y.; Kaneko, T. and Ozawa, T., “A Short Time Method of Thermal Endurance of Insulating Varnish Glass Cloth by Torsional Braid Analysis.” Trans. IEEJ, Vol. 99, 1979, pp. 19-26.

72. Furusho, N.; Komatsu, T. and Nakagawa, T., “A Study of the Thermal Degradation of Several Halogen-containing Polymers by Torsional Braid Analysis.” Bull. Chem. Soc. Japan, Vol. 47, 1974, pp.1573-77.

73. Kaneko, T. and Ozawa, T., “Chemical Kinetic Consideration of Thermal Deterioration of Electrical Insulating Materials Under Cyclic Heating and Cooling.” Trans. IEEJ, Vol. A-97, 1977, pp. 100-107.

74. Yamamoto, Y. and Tanabe, F., “Compatibility of a Magnet Wire Varnish-enamel Combination as a Measure of Thermal Stability of the Insulation System.” Vol. 20, 1979, pp. 26-36.

75. Osuo, S., “Thermal Deterioration of Insulating Varnish.” Joint Convention of Four Electrical Institutes of Japan, S-224, 1969.

76. Sudo, S.; Nanaumi, H. and Tatsui, K., Data for Investigation Committee of Thermal Endurance Test Method on Insulating Materials, No. 49-5, 1970.

77. Investigation Committee of Thermal Endurance Test Method on Insulating Materials, “Examination of Thermal Endurance Testing Models on Insulating Varnishes.” Technical Report of IEEJ (II), No. 28, 1974.

78. Montanari, G.C. and Motori, A., “Thermal Endurance Evaluation of XLPE Insulated Cables.” J. Phys. D: Appl. Phys., 24, 1991, pp. 1172-81.

79. Toop, D.J., “Theory of Life Testing and Use of Thermogravimetric Analysis to Predict the Thermal Life of Wire Enamels.” IEEE Transactions on Electrical Insulation, Vol. 6, 1971, pp. 2-13.

80. Yi, B.; Yingsuo, Z. and Youxiu, M., 1st IEEE ICPADM, 1985, pp. 218-20.

81. Chinese Standard JB1544, 1988.

82. Crine, J.P., “Rate Theory and Polyethylene Relaxations.” IEEE Transactions on Electrical Insulation, Vol. 22, 1987, pp. 169-74.

83. Simoni; Luciano, Fundamentals of Endurance of Electrical Insulating Materials, Editrice Clube Bologona, Italia, 1983.

84. Nakagawa, T., Hopfenberg, H. B., Stannett, V.: J. Appl. Polym. Sci. *15,* 747 (1971).

85. Montanari, G.C. and Lebock, F.J., "Thermal Degradation of Electrical Insulating Materials and The Thermokinetic Background, Theoretical Basis." IEEE Transactions on Electrical Insulation, Vol.25, 1990, pp. 1029-36.

86. Dakin, T.W., AIEE Trans., Vol. 67, 1948, pp. 113-22.

87. Paloniemi, P., "Theory of Equalization of Thermal Aging Processes of Electrical Insulating Materials in Thermal Endurance Tests, Review of Theoretical Basis of Test Methods and Chemical and Physical Aspects of Aging." IEEE Transactions on Electrical Insulation, Vol. 16, 1981, pp. 1-30.

88. Crine, J.P., J. Macromol. Sci. B 23, 1984, pp. 201-19.

89. Crine, J. P., "The Compensation Law Revisited- Applications to Dielectrics Aging." IEEE Transactions on EI, Vol. 26, 1991, pp. 811-8.

90. Watson, K., Private Communication, March 1978.

91. CIGRE - SC 15 Colloquium, Helsinki, 8 Sept. 1977.

92. Fort, E. M. and Pietsch, H. E., "Aging of Insulation by Thermal and Electrical Stresses." Electrical/Electronics Insulation Conference Proc., Nov 1975, pp. 143, IEE Publication No. 75 CH 1014-0-EF54.

93. Campbell, F. J., "Combined Environments Versus Consecutive Exposures for Insulation Life Studies." IEEE Trans., Vol. NS-11, 123 (1964).

94. Densley, John, "Ageing Mechanisms and Diagnostics for Power Cables- An Overview." IEEE Electrical Insulation Magazine, Vol. 17, No. 1, 2001, pp.14-8.

95. Environmental, Health and Safety Issues in the Coated Wire and Cable Industry, Technical Report No. 51, The Massachusetts Toxics Use Reduction Institute, University of Massachusetts Lowell, April 2002.

96. Business Communications Company (BCC), P-133R Outlook for PVC in Major Markets: Highlighting Competitive Scenario, 2000, www.buscom.com.

97. Chemical Economics Handbook, SRI International, 2001.

98. Power Cable Insulation (PVC), www.ciba.com.

99. IEC Publication 216 3rd edn, 1989-1990.

100. Helbert, J. N., N.; Wagner, B. E.; Poindexter, E. H. and Kevan, L.: J. Polym. Sci. A2, 13, 825 (1975).

101. Ohnishi, S., Ikeda, Y., Sugimoto, S., Nitta, I.: J. Polym. Sci. *47,* 503 (1960).

102. Salovey, R., Luongo, J. P., Yager, W. A.: Macromolecules *2,* 198 (1969).

103. Hay, J. N.: J. Polym. Sci. A1, 8, 1201 (1970).

104. Blayden, H. E., Westcott, D. J.: Proc. Fifth Carbon Conf. Pennsylvania State Univ. London: ed. Pcrgamon Press 1963, p. 97.

105. Liebman, S. A., Ahlstrom, D. A., Quinn, E. J., Geigley, A. G., Meluskey, J. T.: J. Polym. Sci. AI, *9,* 1921 (1971).

106. Liebman, S. A., Reuwer, J. F., Gollatz, K. A., Nauman, C. D.: J. Polym. Sci. AI, 9, 1823(1971).

107. Ootani, S., Ishikawa, T.: Kogyo Kagaku Zasshi *66,* 1012 (1963).

108. Ouchi, I.: J. Polym. Sci. AI, *3,* 2685 (1965).

109. Shimokawa, S., Ohno, Y., Sohma, J.: Nippon Kagaku Kaishi *1973,* 2016.

110. Rabek, J. F.; Canback, G.; Lucky, J. and Ranby, B.: J. Polym. Sci. A1 14, 1447 (1967).

111. Tsuchida, E. Shin, C. N., Shinohara, L, Kambara, S.: J. Polym. Sci. AI, *2,* 3347 (1964).

112. Tsuji, K.: Adv. Polym Sci. 12, 131 (1973).

113. Yamamoto, M.; Yano, M. and Nishijima, Y.: Rep. Progr. Polym. Phys. Japan 11, 495 (1968).

114. Dodonov, V. A., Petukhov, G. G., Razuev, G. A.: Izv. Akad. Nauk SSSR *1965,* 1109.

115. Fukuda, K.: Mem. Fac. Sci. Kyushu Univ. Ser. B, 3, 141 (1960).

116. Grishina, A. D. and Bakh, N. A.: Vysokomol. Soedin. 7, 1968 (1965).

117. Ohnishi, S., Sugimoto, S., Nitta, I.: J. Chem. Phys. *39,* 2647 (1963).

118. Tsuji, K., Seiki, T.: J. Polym. Sci. B, 7, 839 (1969).

119. Kobayashi, Kazuharu; Nakayama, Shiroh and Niwa, Toshio, " A New Estimation Method of Thermal History in Crosslinked Polyethylene" Proceedings of the 4th International Conference on Properties and Applications of Dielecric Materials, July 3-8, 1994, pp. 678-81.

120. Montanari, G. C. and Pattini, G., " Thermal Endurance Evaluation of Insulating Materials: A Theoretical and Experimental Analysis" IEEE Transactions on Electrical Insulation, Vol. EI-21, No. 1, February 1986, pp. 69-77.

121. Campbell, D., "Electron Spin Resonance of Polymers" Macromolecular Reviews, Vol. 4, 1970, 91.

122. Bacquet, G.; Dib, J.; Wu, C. Y.; Wertheimer, M. R.; Yelon, A.; Densley, J. R. and Boggs, S. A., "ESR Study of Free Radicals in Electrical Trees in Polyethylene" IEEE Transactions on Electrical Insulation, Vol. EI-13, No. 3, June 1978, pp. 157-63.

123. Tanaka, Tohn, "Insulation Ageing Studies by Chemical Characterization", IEEEE Transactions on Electrical Insulation, Vol. EI-15, No. 3, June 1980, pp. 201-205.

124. www.manufacturingadvice.org.uk/pluto-resources.

125. McCarthy, J., "Panel Discussion Examines Evolution of Thermal Evaluation." Insulation, April 1968, pp. 36-40.

126. Dang, Chinh; Parpal, Jean-Luc and Crine, Jean-Pierre, "Electrical Aging of Extruded Dielectric Cables, Review of Existing Theories and Data." IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 3, No. 2, Apr 1996, pp. 237-47.

127. EPRI Report TR-101660, "Aging of Extruded Dielectric Power Cables: Theory." 1992.

128. Grzybowski, S.; Rakowska, A. and Thompson, J. E., “Aging of Polyethylene for Cable Insulation.” IEEE Transactions on Electrical Insulation, Vol. EI-22, No. 6, Dec 1987, pp. 729-34.

129. IEC 15B (10) Document 1988 (becoming IEC Report 1026), 1990.

130. Montanari, G. C.; Pattini, G. and Simoni, L., "Long Term Behavior of XLPE Cable Models." IEEE/PES Summer Meeting, paper SM396.6, 1986.

VITA

Ali Muhammad Ali Abu-Gurain, received the B.S. Degree in Electrical Engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, in 1996. He joined KFUPM in 1996 as a part-time student in the M.S. program and completed the M.S. degree in June 2003. At present, he is working at Ministry of Water and Electricity, Water General Directorate - Eastern Province.