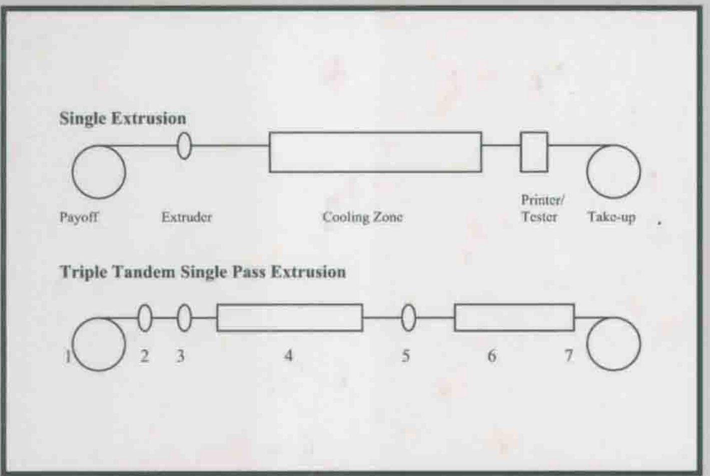
Electrical Power Cable Engineering

Second Edition, Revised and Expanded



edited by

William A. Thue

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Second Edition, Revised and Expanded

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MARCEL DEKKER, INC. NEW YORK • BASEL

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Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress.

ISBN: 0-8247-4303-2

This book is printed on acid-free paper.

Headquarters
Marcel Dekker, Inc., 270 Madison Avenue, New York, NY 10016, U.S.A.
tel: 212-696-9000; fax: 212-685-4540

Distribution and Customer Service
Marcel Dekker, Inc., Cimarron Road, Monticello, New York 12701, U.S.A.
tel: 800-228-1160; fax: 845-796-1772

Eastern Hemisphere Distribution
Marcel Dekker AG, Hutgasse 4, Postfach 812, CH-4001 Basel, Switzerland
tel: 41-61-260-6300; fax: 41-61-260-6333

World Wide Web
http://www.dekker.com

The publisher offers discounts on this book when ordered in bulk quantities. For more information, write to Special Sales/Professional Marketing at the headquarters address above.

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Current printing (last digit):

10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

Electrical Power Cable Engineering

POWER ENGINEERING

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SERIES INTRODUCTION

Power engineering is the oldest and most traditional of the various areas within electrical engineering, yet no other facet of modern technology is undergoing a more dramatic revolution in both technology and industry structure. Among the most important electrical technologies for the 21st century is power cable engineering. Insulated cable has become a staple of modern power engineering and operations, where underground power transmission keeps facilities out of sight and largely protected from external damage. Increasingly, the use of insulated cable rather than air-insulated overhead conductor is the only acceptable way for electric utilities to move power in both heavily congested urban cores and environmentally or esthetically important areas. And increasingly, the maintenance, care, and condition assessment of older cable, cable that has been in service for twenty or thirty years, is a particular concern to modern utilities. That, among other topics, is part of the expanded focus of *Electric Power Cable Engineering, Second Edition.*

This second edition is a thorough, well-organized treatment of modern power cable engineering, applications, and practices, as was the first. But this second edition has grown in company with both the electric industry itself and the field of cable engineering, and consequently it provides new focus on condition assessment, lifetime extenuation, and cable characteristics and applications. As before, the book focuses on practical, rigorous engineering and operation of low- and medium-voltage cables, that constitute the vast majority of industry need. As before, the book is organized and well cross-referenced so that it makes an excellent reference for practicing engineers, yet has a very modular and serial development of its content in order to be an excellent text for engineering courses or for self-paced tutorial study.

As the editor of the Power Engineering Series, I have always been proud that William Thue's book was included in the series, and it is particularly satisfying to see the important books in the series keep pace with the industry and technology through a constant process of revision and expansion. Like the other volumes, *Power Cable Engineering, Second Edition,* continues to put modern technology in a context of proven, practical application as a reference, for self-study, and for advanced classroom use. The Power Engineering Series includes books covering the entire field of power engineering, in all its specialties and subgenres, all aimed at providing practicing power engineers with the knowledge and techniques they need to meet the electric industry's challenges in the 21st century.

H. Lee Willis

FOREWORD

Electrical cable might be considered to be just a conductor, overlying insulation, and often an exterior shield or jacket. Perhaps this naive, simplistic concept is part of the reason that cable engineering, especially for power cable, has been largely neglected by recent electrical engineering education in the United States with its emphasis on computers, electronics, and communication. But power cable does electrically connect the world! The history, so interestingly presented, shows how the subject evolved with both great success and sometimes unexpected failure.

As this book emphasizes, cable engineering is technically very complex. Certainly electrical, mechanical, and even to some extent civil engineering are involved in interrelated ways. Many other disciplines—physics, inorganic chemistry, organic (primarily polymer) chemistry, physical chemistry, metallurgy, corrosion with tests and standards in all of these areas—are of concern. Of course, it is impossible in one book to deal with all of these aspects in a completely comprehensive way. However, the various components of power cables are considered with sufficient detail to provide an understanding of the basic considerations in each area. Reference to detailed sources provides a means for those with greater interest to pursue specific subjects.

The importance of factors involved in different types of cable installation is stressed. Long vertical cable runs have special problems. Installation in ducts may lead to problems with joints, terminations, elbows, and pulling stresses. At first, cable with extruded insulation was buried directly in trenches without recognizing the then unknown problem of "water treeing" in polyethylene, which was originally thought to be unaffected by moisture. After massive field failures, well over a thousand papers have been written on water treeing! Field failures can involve many factors, e.g., lightning, switching surges, repeated mechanical stressing, and swelling of voltage grading shields in contact with organic solvents such as oil and gasoline. It is important to recognize how such diverse factors can affect the performance of cable in the field.

Electrical Power Cable Engineering, Second Edition meets a need to consider its complex subject in a readable fashion, especially for those with limited background and experience. Yet, sufficient detail is provided for those with greater needs in evaluating different cables for specific applications. Most of all, the supplier of materials for cables can obtain a better understanding of overall problems. On the other side, the experienced cable engineer will learn the parameters of materials with which he or she was not fully familiar.

Kenneth N. Mathes
Consulting Engineer
Schenectady, New York

PREFACE

A course entitled Power Cable Engineering Clinic was presented at the University of Wisconsin – Madison from the early 1970s until the emphasis and title was changed in 1999. The course has been reorganized and is now "How to Design, Install, Operate, and Maintain Reliable Power Cable Systems." It is divided into two sessions: "Understanding Power Cable Characteristics and Applications" and "Assessing and Extending the Life of Shielded Power Cable Systems." Numerous lecturers have produced copious class notes that form the basis for much of the material that is contained in this book. The contributors hope that their team effort will provide a useful addition to the library of all dedicated cable engineers.

The dynamics of the cable industry produces many new materials, products, and concepts that are incorporated in this second edition. Several new chapters have been prepared (Thermal Resistivity of Concrete, Underground System Fault Locating, Armor Corrosion of Submarine Cables, and Semiconducting Jackets) and others have been greatly expanded and revised from the first edition (Electrical Insulating Materials and Field Assessment of Power Cables).

The emphasis of this book is on low and medium voltages since they comprise the greatest quantity of cable in service throughout the world. Transmission cables have the greater sophistication from an engineering standpoint, but all the basic principles that apply to transmission cables also apply to the lower-voltage cables.

This second edition covers the up-to-date methods of design, manufacture, installation, and operation of power cables. The audience that would benefit from the highly knowledgeable writings and diversity of backgrounds of the contributors to this book includes:

> Cable engineers and technicians employed by investor-owned utilities, rural electric cooperatives, industrial users, and power production personnel

> Universities that offer electrical power courses

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Cable manufacturers that would like to provide their employees with an overview and understanding of power cables

The text provides the information that is required to understand the terminology and engineering characteristics and background of power cables and to assist in making sound decisions for specifying, purchasing, installation, maintenance, and operation of electrical power cables.

William A. Thue

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CHAPTER 1

HISTORICAL PERSPECTIVE OF ELECTRICAL CABLES

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1.0 DEVELOPMENT OF UNDERGROUND CABLES

In order to trace the history of underground cable systems, it is necessary to examine the early days of the telegraph [1-1, 1-2]. The telegraph was the first device utilizing electrical energy to become of any commercial importance and its development necessarily required the use of underground construction. Experimentation with underground cables accordingly was carried on contemporaneously with the development of the apparatus for sending and receiving signals. Underground construction was planned for most of the earliest commercial lines. A number of these early installations are of considerable interest as marking steps in the development of the extensive underground power systems in operation around the world.

2.0 EARLY TELEGRAPH LINES

In 1812, Baron Schilling detonated a mine under the Neva River at St. Petersburg, Russia, by using an electrical pulse sent through a cable insulated with strips of India rubber. This is probably the earliest use of a continuously insulated conductor on record.

One of the earliest experiments with an underground cable was made by Francis Ronalds in 1816. This work was in conjunction with a system of telegraphy consisting of 500 feet of bare copper conductor drawn into glass tubes, joined together with sleeve joints and sealed with wax. The tubes were placed in a creosoted wooden trough buried in the ground. Ronalds was very enthusiastic over the success of this line, predicting that underground conductors would be widely used for electrical purposes, and outlining many of the essential characteristics of a modern distribution system.

The conductor in this case was first insulated with cotton saturated with shellac before being drawn into the tubes. Later, strips of India rubber were used. This installation had many insulation failures and was abandoned. No serious attempt was made to develop the idea commercially.

In 1837, W. R. Cooke and Charles Wheatstone laid an underground line along the railroad right-of-way between London's Euston and Camden stations in London for their five-wire system of telegraphy. The wires were insulated with cotton saturated in rosin and were installed in separate grooves in a piece of timber coated with pitch. This line operated satisfactorily for a short time, but a number of insulation failures due to the absorption of moisture led to its abandonment. The next year, Cooke and Wheatstone installed a line between Paddington and Drayton stations, but iron pipe was substituted for the timber to give better protection from moisture. Insulation failures also occurred on this line after a short time, and it was also abandoned.

In 1842, S. F. B. Morse laid a cable insulated with jute, saturated in pitch, and covered with strips of India rubber between Governor's Island and Castle Garden in New York harbor. The next year, a similar line was laid across a canal in Washington, D.C. The success of these experiments induced Morse to write to the Secretary of the Treasury that he believed "telegraphic communications on the electro-magnetic plan can with a certainty be established across the Atlantic Ocean."

In 1844, Morse obtained an appropriation from the U. S. Congress for a telegraph line between Washington and Baltimore. An underground conductor was planned and several miles were actually laid before the insulation was proved to be defective. The underground project was abandoned and an overhead line erected. The conductor was originally planned to be a #16 gage copper insulated with cotton and saturated in shellac. Four insulated wires were drawn into a close fitting lead pipe that was then passed between rollers and drawn down into close contact with the conductors. The cable was coiled on drums in 300-foot lengths and laid by means of a specially designed plow.

Thus, the first attempts at underground construction were unsuccessful, and overhead construction was necessary to assure the satisfactory performance of the lines. After the failure of Morse's line, no additional attempts were made to utilize underground construction in the United States until Thomas A. Edison's time.

Gutta-percha was introduced into Europe in 1842 by Dr. W. Montgomery, and in 1846 was adopted on the recommendation of Dr. Werner Siemens for the telegraph line that the Prussian government was installing. Approximately 3,000 miles of such wire were laid from 1847 to 1852. Unfortunately, the perishable nature of the material was not known at the time, and no adequate means of protecting it from oxidation was provided. Insulation troubles soon began to

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