UNDERGROUND SYSTEMS REFERENCE BOOK

Po

UNDERGROUND SYSTEMS REFERENCE BOOK

PREPARED BY AN EDITORIAL STAFF
OF THE EDISON ELECTRIC INSTITUTE
TRANSMISSION AND DISTRIBUTION COMMITTEE

1957

Published by the

EDISON ELECTRIC INSTITUTE

420 LEXINGTON AVENUE NEW YORK 17, N.Y.

EEI Publication No. 55-16
First Printing—10,000 copies

PRINTED IN THE UNITED STATES OF AMERICA
BY THE COLONIAL PRESS INC., CLINTON, MASS.

EDITORIAL STAFF

J. A. Pulsford, *Editor-in-Chief*
Public Service Electric and Gas Company

C. C. Knox, *Associate Editor-in-Chief*
Peter F. Loftus Corporation

E. T. Carmichael, *Assistant to the Editors*
Public Service Electric and Gas Company

Introduction

A. H. Kidder, *Editor*........Philadelphia Electric Company

Assistant Editors

W. A. Del Mar...Phelps Dodge Copper Products Corporation
C. W. Franklin...Consolidated Edison Company of New York, Inc.
L. F. Hickernell.........Anaconda Wire & Cable Company
R. J. Wiseman.....................The Okonite Company

Chapter 1—Applications for Cable and Cable Systems

D. Burns, *Editor*.............The Detroit Edison Company

Assistant Editors

D. K. Blake.....................General Electric Company
P. H. Jeynes........Public Service Electric and Gas Company
W. C. Phillips.......New England Power Service Company
E. A. Rothfus......................Ohio Edison Company

Consultant

G. J. Crowdes...........Simplex Wire and Cable Company

Chapter 2—Cable and Cable Insulation

E. W. Davis (deceased), *Editor*.....Simplex Wire and Cable Company
R. J. Wiseman, *Associate Editor*.....The Okonite Company

Assistant Editors

G. J. Crowdes...........Simplex Wire and Cable Company
W. A. Del Mar...Phelps Dodge Copper Products Corporation
L. F. Hickernell.........Anaconda Wire & Cable Company
G. Thompson............Electric Testing Laboratories, Inc.

Consultant

C. F. Avila.......................Boston Edison Company

Chapter 3—Bulk Power Systems

W. R. Bullard, *Editor*........Ebasco Services Incorporated

Assistant Editors

T. W. Eisenman..................Electrical Constructors
C. T. Hatcher...Consolidated Edison Company of New York, Inc.
R. A. Horenburger.........Philadelphia Electric Company
F. M. Hull..................The Detroit Edison Company
W. H. Salle...............Commonwealth Edison Company
P. L. Weir...............Potomac Electric Power Company

Consultants

M. D. Bergan........The Thomas & Betts Co., Incorporated
G. N. Everest.......................The Okonite Company
M. H. McGrath................General Cable Corporation
E. J. Merrell....Phelps Dodge Copper Products Corporation
J. H. Nicholas..........G & W Electric Specialty Company
P. V. White.......................Henry Ihle, Incorporated

Chapter 4—Underground Radial and Loop Systems

W. P. Holben, *Editor*...........Duquesne Light Company

Associate Editors

(Section A) C. T. Nicholson.......Niagara Mohawk Power Corporation
(Section B) J. J. Rueckert...Baltimore Gas and Electric Company
(Section C) F. E. Andrews...Commonwealth Edison Company

Assistant Editors

J. A. Cooney.........The Hartford Electric Light Company
L. D. Cronin...............Ebasco Services Incorporated
P. W. Crosby...............Philadelphia Electric Company
L. J. Dylewski..........G & W Electric Specialty Company
F. W. Smith..........Virginia Electric and Power Company
J. H. Stoneman.......Virginia Electric and Power Company
R. K. Woodson.......Kansas City Power & Light Company

Consultants

E. B. Buster.......................S & C Electric Company
H. C. Carless......Allis-Chalmers Manufacturing Company
H. W. Dornbush......Pennsylvania Transformer Company
F. Heller..................Burndy Engineering Company
G. F. Lincks..................General Electric Company
M. H. McGrath..................General Cable Corporation
J. B. Owens...............ITE Circuit Breaker Company
F. C. Van Wormer.............General Electric Company

Chapter 5—Underground Secondary Networks

W. P. Holben, *Editor*...........Duquesne Light Company
S. L. Woolley, *Associate Editor*....Duquesne Light Company

Assistant Editors

H. G. Barnett.......................Oregon State College
B. S. Beall, III.................General Electric Company
H. W. Clark............Potomac Electric Power Company
G. G. Grissinger.......Westinghouse Electric Corporation
N. M. Neagle...............General Electric Company
J. C. Quayle...The Cleveland Electric Illuminating Company
E. L. Woods.....................General Electric Company

Consultants

F. Heeler.................Burndy Engineering Company
J. B. Hodtum....Allis-Chalmers Manufacturing Company
H. F. Lawrence.........Westinghouse Electric Corporation
A. R. Lee.....................General Electric Company
G. R. Murray...........Westinghouse Electric Corporation

Chapter 6—Street Lighting Systems

A. E. Stant, *Editor*......Potomac Electric Power Company

Assistant Editors

T. M. Barr...Central Hudson Gas and Electric Corporation
A. T. Green..........Niagara Mohawk Power Corporation
H. T. Hofer..........Public Service Company of Colorado
H. L. Livingood...New York State Electric & Gas Corporation
M. W. McRaven.......Houston Lighting & Power Company
O. Moberg.........The Hartford Electric Light Company

Consultants

W. F. Blackford......................Line Material Company
L. F. Heckmann...The Union Metal Manufacturing Company
E. B. Karns...........Westinghouse Electric Corporation
A. R. Lee.....................General Electric Company
J. Peterson....................General Electric Company
L. P. Schmitt.........................The Joslyn Company
R. M. Swetland.................General Electric Company

Chapter 7—Conduits and Manholes

R. E. Morse, *Editor*....American Gas and Electric Company

Assistant Editors

A. Bodicky........................Union Electric Company
R. L. Bryan...........Southern California Edison Company
N. G. Harrison, Jr.........Nat G. Harrison, Jr. & Associates
L. G. Kraft.................Philadelphia Electric Company
W. A. Thue..............Florida Power & Light Company
E. G. Watkins...Consolidated Edison Company of New York, Inc.

Consultant

W. T. Peirce...American Steel and Wire Division, United States Steel Corporation

Chapter 8—Cable Installation

C. S. Schifreen, *Editor*......Philadelphia Electric Company

Assistant Editors

L. G. Atkinson......Rochester Gas and Electric Corporation
A. Bodicky........................Union Electric Company
H. E. Dodds................Commonwealth Edison Company
C. D. Eash....................Consumers Power Company
G. H. Landis...Central Hudson Gas and Electric Corporation
A. G. Pergande..........Wisconsin Electric Power Company
J. P. Woodward...................Union Electric Company

Consultant

S. Zysk..........................General Electric Company

Chapter 9—Cable Joints and Terminations

F. P. West, *Editor*....Consolidated Edison Company of New York, Inc.

Assistant Editors

J. A. Berner.............Northern States Power Company
R. F. Burnham...........The Connecticut Power Company
W. P. Cook.......................Duquesne Light Company
F. D. Crawford...Consolidated Edison Company of New York, Inc.
J. E. Johnson..............Philadelphia Electric Company
F. C. LaGioia...Consolidated Edison Company of New York, Inc.
H. E. Martin...Waterbury Company, Inc., Cable Service Division
E. J. Nelson........Rochester Gas and Electric Corporation
J. H. Nicholas..........G & W Electric Specialty Company

Consultants

W. S. Brown...........G & W Electric Specialty Company
F. Heller..................Burndy Engineering Company
R. C. Waldron.......................The Okonite Company

Chapter 10—Cable and Underground Equipment Loading

H. Halperin and C. A. Jaques, *Editors*......Commonwealth Edison Company
D. D. Nagley, *Associate Editor*......Commonwealth Edison Company

Assistant Editors

A. Bodicky........................Union Electric Company
F. H. Buller....................General Electric Company
R. W. Burrell...Consolidated Edison Company of New York, Inc.
E. H. Kirkham...Phelps Dodge Copper Products Corporation
O. N. Yeary................Texas Electric Service Company

Consultants

B. S. Beall III.................General Electric Company
M. F. Beavers..................General Electric Company
H. C. Carless.......Allis-Chalmers Manufacturing Company
G. G. Grissinger.........Westinghouse Electric Corporation
M. H. McGrath................General Cable Corporation
F. C. Roeding............Westinghouse Electric Corporation

Chapter 11—Cable Testing, Fault Location and Cable Identification

C. B. Bechtel, *Editor*...Baltimore Gas and Electric Company

Assistant Editors

E. B. Curdts.......................J. G. Biddle Company
R. S. Diggs.................Philadelphia Electric Company
L. A. Gray...............Simplex Wire and Cable Company
H. B. Slade........................The Okonite Company

Chapter 12—Records, Repairs and Maintenance

G. T. Hays, *Editor*..........Dallas Power & Light Company

Assistant Editors

S. C. Anderson..........Pacific Gas and Electric Company
F. D. Crawford...Consolidated Edison Company of New York, Inc.
E. F. Nuezel.......The Cincinnati Gas & Electric Company

Chapter 13—Cable and Equipment Reconditioning

R. C. Blankenburg, *Editor*......Southern California Edison Company

Assistant Editors

W. P. Cook.......................Duquesne Light Company
B. W. Hafeli.................The Detroit Edison Company

Consultant

E. J. Merrell...Phelps Dodge Copper Products Corporation

Chapter 14—Corrosion

H. W. Wahlquist, *Editor*......Ebasco Services Incorporated
B. C. Lattin, *Associate Editor*...Ebasco Services Incorporated

Assistant Editors

J. C. Howell...Public Service Electric and Gas Company
F. E. Kulman...Consolidated Edison Company of New York, Inc.

Consultant

B. R. Hubbard...Triangle Conduit and Cable Company, Inc.

Chapter 15—Safety Practices

G. H. Fiedler, *Editor*..........Rochester Gas and Electric Corporation
W. F. Brown, *Associate Editor*.........Consolidated Edison Company of New York, Inc.

Assistant Editors

H. E. Hatfield...................Georgia Power Company
R. E. McCann.........Southern California Edison Company

Consultant

S. J. Rosch..............Anaconda Wire & Cable Company

Bibliography

L. E. Fogg.............Kennecott Wire and Cable Company

Review Board

C. F. Avila........................Boston Edison Company
W. R. Bullard................Ebasco Services Incorporated
E. N. Clark.......Pioneer Service and Engineering Company
H. E. Cody....The Cleveland Electric Illuminating Company
G. H. Fiedler.......Rochester Gas and Electric Corporation
D. C. Hawley.........Kansas City Power & Light Company
E. B. Shew.................Philadelphia Electric Company

PREFACE

The Transmission and Distribution Committee of the Edison Electric Institute is proud to present to the Electric Power Industry the first revision of the NELA Underground Systems Reference Book, originally published in 1931.

Completely rewritten, the book has been prepared for both field and office use. Reflecting the extensive developments of the past quarter of a century, it is believed that it presents a comprehensive and practical study of the best practices in design, construction, operation and maintenance of power cable systems.

This revised edition, which retains only a small portion of the original historical information, is about twice as large as the original work. It was prepared by a staff of 134 over a period of three years. The first edition was four years in preparation and 45 persons collaborated in its writing. Seven of the contributors to the original book also contributed to the present revision. They are Messrs. D. K. Blake, H. S. Davis, W. A. Del Mar, C. W. Franklin, H. Halperin, C. C. Knox and L. G. Kraft.

In its preparation, every effort was made to have the text non-regional in character. Engineers from widely separated localities were appointed to each chapter staff and the material submitted was reviewed by men from still other sections of the country. Standards, specifications and instructions were solicited from 34 utility companies having the largest underground systems and were distributed to the interested chapter editors. Questionnaires were circulated to collect information not adequately covered by individual company standard practices.

Practices and descriptions of equipment common to both underground and overhead construction have been included to give complete coverage of certain subjects. All widely used practices known to the editors have been described without prejudice to the end that the reader may select the practices best adapted to his particular conditions.

For certain subjects, such as economic studies, it was not feasible to provide full treatment, but references to pertinent material published elsewhere have been included. Tables, statistics and general data readily available in standard reference books have been omitted.

We take this occasion to thank the many well-known and busy engineers who have contributed the time and effort for the preparation of this volume. A small part of their work may have been done during office hours, but the bulk was accomplished outside of the regular working day. We are also deeply indebted to the many utility companies and manufacturers who supported the project by generous contributions of both technical and non-technical manpower, as well as service and material necessary for the completion of this reference book. We are also grateful to AIEE, IPCEA, AEIC and other associations and publishers for their contribution of material which has been reproduced in the reference book and for their sympathetic cooperation with the entire undertaking. A considerable amount of work was done by men who were not members of the Editorial Staff. Our sincere thanks are extended to all of these unknown soldiers. We are also grateful for the help of other committees of Edison Electric Institute.

We have found the work of preparation a most enjoyable assignment. Members of the staff and other contributors have been most gracious in resolving differences of opinion and have been both prompt and thorough in completing their assignments.

During the three years of work on the book we have lost one member of the staff. Mr. E. W. Davis, then President of IPCEA, died in 1955 after his Chapter 2 was basically complete. He was one of our most enthusiastic workers and we deeply regret that he was not destined to see the finished product.

James A. Pulsford, Editor-in-Chief
Carlos C. Knox, Associate Editor-in-Chief

This book is divided into chapters, each chapter having its own sequence of page numbers. For instance, 4-9 indicates Chapter 4, page 9.

Superior numerals in the text of a chapter indicate the numbers of references cited in the Bibliography appearing at the end of that chapter.

INTRODUCTION

The power distribution function basically includes all of the facilities and services associated with the delivery to consumers, of power made available at some central generating or receiving point.

For convenience it has become customary on occasion to refer to various components of the distribution system as transmission, subtransmission, primary distribution and secondary distribution facilities, although each contributes its part to the over-all distribution function. With the passage of time and accompanying increases in load density, together with advances in the art, circuits having voltages originally considered so high as to be suitable only for transmitting scheduled blocks of power from one place to another, have long since been used extensively as distribution circuits, for power delivery to consumers whose momentarily changing demands alone determine the loads on the circuits.

By this process of evolution some, if not all, present-day transmission voltages will become future distribution voltages. Hence, considerable confusion can be avoided by accepting the fact that the transmission or "send across" function basically applies only to facilities used for scheduled bulk power transfers between stations which have been interconnected for reasons usually associated with economy in fuel and generating capacity costs. All other facilities essentially perform the distribution function.

Overhead and underground distribution systems both perform the same basic function, although their design and operation involve quite different techniques. Both systems include various types of lateral, branch and radial circuits, some of which will operate in parallel after a fashion commonly referred to as a "network." As the title of this reference book implies, it has to do almost exclusively with the particular group of specialties, skills and techniques of designing, constructing, operating and maintaining underground systems.

One significant difference between open-wire and cable circuits lies in the fact that cable conductors must be covered by an insulating material throughout their entire length for the full operating voltage of the circuit, whereas open-wire circuits are insulated by air, except at terminations and at intermediate points of support. Hence, the challenges to be met by the designer of underground systems have centered largely about this problem of conductor insulation. Aerial cable installations are so similar to underground cables that they have been treated in this book. There are also many other problems associated with corrosion, heat dissipation, safety and providing needed accessibility for maintenance or replacement. Of course it will be understood that other distribution equipment, as well as cables and their accessories, must all be designed to permit satisfactory installation and maintenance.

The responsibilities of the engineer include, among other things, the practice of sound stewardship in making designs which provide the required quality of service at the lowest total cost. Since underground construction is an expensive alternative for overhead installation, it follows naturally that an underground system should be specified only in those areas where considerations of public welfare, safety, very high load density or architectural environment are unquestionably sufficient to warrant the greater cost. Consequently, very few power distribution systems are installed wholly underground. Even in areas served predominantly by aerial systems, however, it is often necessary to avoid intolerable overhead congestion by the underground installation of high-capacity feeders, particularly in the vicinity of major distribution centers.

With each passing year, therefore, systems having had little previous experience with underground construction are finding themselves confronted with the inescapable necessity of entering a new field of specialized practice in which a tremendous amount of talent and effort has brought about almost revolutionary development during the quarter century since publication of the last *Underground Systems Reference Book*. The great strides which have been made toward developing package equipment, which can be installed with a minimum of field labor, have had little effect upon reducing the amount of extremely specialized skill and care required for the field installation of cable, joints and terminals in environments where the procedures required to avoid contamination seem almost impossible of attainment. The integrity of an underground cable system, therefore, continues to be extraordinarily dependent upon excellence of workmanship in the field installation.

HISTORICAL DEVELOPMENT

Distribution of electricity by underground systems was started by the early telegraphers, among them Ronalds, Wheatstone and Morse. Insulated wires buried in the ground and wires drawn into conduits were tried with varying success. Francis Ronalds, in 1816, used bare copper wires drawn into glass tubes placed in a buried wooden trough. W. F. Cooke and Charles Wheatstone, in 1837, placed insulated wires in grooves in buried timber. In 1844 S. F. B. Morse buried some miles of lead sheathed cable between Washington and Baltimore but abandoned it in favor of an overhead line. None of these early lines proved to be successful due to the hygroscopic nature of the only insulations then available. The best of these was gutta-percha, but it was too prone to oxidation in the absence of adequate protection from the air.

Very little was done in the way of underground distribution from the early days of the telegraph until the advent of Edison's electric lighting, a period of nearly 40 years.

Arc lighting by Jablochkoff, Brush and others, in the 1870's, used overhead wires at about 2000 v, the lamps being connected in series.

Lighting by incandescence was principally the result of the work of Edison who developed a complete system of lighting by this method in 1879, in which the lights were designed to operate in parallel.

Edison planned his first installation for New York City and decided that an underground system of distribution would be necessary. This took the form of an electrically interconnected network of low-voltage distribution mains supplied by feeders radiating from a centrally located d-c generating station to various feeding points in the network.

Edison designed a rigid buried system consisting of copper rods insulated with a wrapping of jute. Two or three insulated rods were drawn into iron pipes and a heavy bituminous compound forced in around them. They were laid in 20-ft sections and joined together with specially designed tube joints from which taps could be taken if desired. The Edison tube gave remarkably satisfactory performance for this class of service.

The low-voltage, heavy-current characteristic of d-c distribution limited the area that could be supplied from one source, if the voltage regulation were to be kept within reasonable bounds. Moreover, the high first cost and the heavy losses have made such systems uneconomical for general distribution. Therefore, they developed in limited areas of high load density, such as the business districts of the larger cities, and even in these areas, subsequent load growth has largely compelled replacement by a-c systems.

The now almost universally employed a-c system of distribution was developed largely as the result of the work of L. Gaulard and J. D. Gibbs, who in 1882 designed a crude alternating-current system using induction coils as transformers. The primary coils at first were connected in series for high-voltage transmission. Satisfactory performance could not be obtained because the reactance of the transformers was not taken into account, but they were able to distribute electric energy at a voltage considerably higher than that required for lighting, and to demonstrate the economies attending its use. The system was introduced into the United States in 1885 by George Westinghouse. An experimental installation went into service at Great Barrington, Mass., early in 1886. The first large scale commercial installation was made at Buffalo, N. Y., the same year.

The early a-c installations operated at 1000 v. Overhead construction was considered essential for their satisfactory performance and almost universally employed.

In the course of a few years the installations of overhead wires for telegraphs, telephones, street lighting, etc., led to congestion and unsightliness which emphasized the need for considering underground construction. In 1888 the situation was summarized in a paper before the National Electric Light Association as follows:

> No arc wires had been placed underground in either New York or Brooklyn. The experience in Washington led to the statement that no insulation could be found that would operate two years at 2000 v. In Chicago all installations failed with the exception of lead-covered cables which appeared to be operating successfully. In Milwaukee three different systems had been tried and abandoned. In Detroit a cable had been installed in Dorsett conduit but later abandoned. In many larger cities low-voltage cables were operating satisfactorily and in Pittsburgh, Denver, and Springfield, Massachusetts, some 1000-v circuits were in operation.

After studying the available data the New York Subway Commission decided to adopt rubber-insulated, lead-covered cable installed in ducts for the street lighting circuits. This general type of system became standardized throughout the country, although paper-insulated cables later became the preferred design.

The advantages to be obtained from the use of conduits into which insulated conductors could be drawn or removed without disturbing the surface of the street became apparent when many of the earlier cable installations had to be completely replaced soon after their installation.

The first rubber insulation was unvulcanized and had very short life. An improvement was made by mixing the rubber with vulcanized vegetable oil, known as factice, and, although Goodyear had patented vulcanized rubber in 1844, it was not until 1860, however, that vulcanized rubber insulation came into general use on telegraph systems and not until the late 1880's for electric lighting cables. During this interval, a successful insulation containing rubber was developed under the trade name of Kerite, which became the forerunner of today's high-voltage rubber-base insulations.

The Cataract Power and Conduit Co., of Buffalo, N. Y., still doubtful about paper, adopted Dr. Habirshaw's rubber insulation for its 11,000-v lines in 1897. The last of these cables was removed in 1928.

This was followed in 1900 by Henry Floy's 25,000-v rubber-insulated cable at St. Paul and Minneapolis, but, thereafter, rubber was used on few high-voltage underground systems.

A paper-wrapped wire that developed into the present-day cable was made about 1872 by a paper manufacturer of Richmond, Va., named John H. Wortendyke, who used it for an electric bell system in his home. Wortendyke made a crude taping machine for this purpose but apparently made no attempt to commercialize his wire. About 1883 Wortendyke had in his employ one Edwin D. McCracken, who made further developments in the taping machine and applied for a patent in February, 1884, which was granted as Number 304,539, September 2, 1884. This patent covered: "An electric wire having a covering consisting of a spirally wound and lapping strip or strips of paper composed of pure vegetable fiber and applied in its unchanged fibrous condition to the wire, the paper forming, of itself, the insulating covering for the wire."

McCracken and his associates organized and reorganized a series of unsuccessful companies to promote his patent: First, the Norwich Insulated Wire Co., of Norwich, N. Y., and finally of Harrison, N. J.

The first impregnated-paper cable having helically applied paper tapes, oil impregnation and a lead sheath extruded over the core was a telephone cable designed by John A. Barrett, of the American Telephone and Telegraph Co.

The impregnation of this cable was effected by mere immersion in hot oil in the expectation that the heat would drive out the moisture by evaporation and the air by expansion. It was J. T. Jaques, of Boston, Mass., then associated with the Faraday Electric Cable Co., who patented in 1885 a process combining vacuum drying with hot impregnation under pressure.

The Norwich Wire Co. began to sell the product of its Harrison plant in 1887, acquired a lead press in 1890 and sold out to the National Conduit and Cable Co. in 1891.

While flexible cables insulated with paper tapes and impregnated with oil were being developed for low voltages in America, Ferranti, in England in 1890, following the Edison example of using rigid mains, took the daring step at Deptford of using paper for the hitherto unthought of voltage of 10,000 v, single phase. These mains, made in 20-ft lengths, consisted of two concentric tubes of copper insulated by single wide sheets of brown paper steeped in Ozokerite, both between the tubes and over the outer tube, the whole enclosed in an iron pipe. The pipe was drawn down through a die plate until it fitted tightly over the insulation. These mains were buried under the streets and joints were provided between the 20-ft lengths. They remained in service, at least in part, until 1933.

The success of Ferranti's daring Deptford mains installation fortunately helped the cause of cables more than that of rigid tubes. McCracken's patent on wire insulated with paper tape, which was six years old at the time of this installation, came to be noticed and people began to ask whether taped cable might not be good for 3000 v or even 6600 v, if rigid conductors insulated with wide sheets were good for 10,000 v.

The year 1895 marks the practical beginning of impregnated-paper cable. Shortly afterward several companies started its manufacture. The first 13,000-v paper-insulated cable was made by the National Conduit and Cable Co. in 1897, and installed at Minneapolis and St. Paul, Minn. This American development represented a significant departure from the rigid construction previously employed by Ferranti at Deptford. Thereafter, developments in Europe closely paralleled those in America.

Progress was rapid between 1895 and 1898, for on December 30, 1898, we find Alex. Dow writing as follows in *Engineering News:* "Electric light practice today is about evenly divided between paper-insulated cables and rubber-insulated cables, both lead covered."

That the uncertainty about paper persisted to 1899, when a 25,000-v system was projected for St. Paul and Minneapolis, is shown by the fact that both rubber and paper cables of that voltage were installed on that system in 1900. It is of interest to note that the paper cable remained in use until the line was redesigned in 1928.

By 1902 paper insulation was fully established and, substantially unchanged from its original type, proved adequate to all needs until the time of World War I, when the use of electricity increased with unprecedented rapidity and introduced new loading conditions.

The early cables were impregnated with a mixture of rosin oil, known as London Oil, and wood rosin. This was superseded shortly after World War I by a mixture of petrolatum and rosin and finally, in the middle 1920's, by a viscous fluid mineral oil with or without refined rosin or polyisobutylene.

The necessity for transferring large

blocks of power over tie lines created a much greater need than formerly for cables capable of being operated at transmission voltages. This increased demand for high-tension cables resulted in a widespread interest in the subject and was met by a number of important developments in cable manufacture.

The first steps to accomplish these ends included the use of higher vacua to dry and degasify the insulation and obtain more thorough impregnation, an aim which was also assisted by careful temperature and pressure controls, all of which involved the development and installation of improved equipment. These developments led both to greater reliability of operation and to increased carrying capacity due to increased dielectric strength and reduced dielectric loss.

Shielded cable, patented by Martin Hochstadter in 1916, came to the fore in the middle 1920's for multiple-conductor construction for 15,000 v and above and, at about the same time, engineers became conscious of the formation of voids due to the expansion and contraction of the impregnant and resorted to the oil-filled cable system of Luigi Emanueli for the higher voltages. This system, using a very fluid oil and reservoirs to accommodate its thermal expansion, enabled transmission voltages to be raised from 69,000 to 138,000 in America and to 220,000 in Europe.

A patent by H. W. Fisher and R. W. Atkinson, in 1927, revealed that the dielectric strength of impregnated-paper insulation could be greatly increased by maintaining it under pressure. This principle was not put to practical use until 1932, when a commercial installation of cable operating at 200 psi was built in London. In the same year an experimental line was installed near Philadelphia. In both of these systems, the cables were installed in steel pipes, the English using nitrogen gas as the pressure medium and the Americans, oil.

Following the first commercial installation of pipe cable in America in 1934, pipe cables using either type of pressure medium have become accepted and since 1946 have come into extensive use for the higher voltages.

Varnished cambric is a tape insulation introduced shortly before World War I, consisting of cotton cloth covered on both sides with varnish, with oil or grease known as "slipper" applied between tapes. It is much more water absorbent than rubber and, unless protected by a waterproof sheath, is not suitable for use in damp locations. Its use in underground systems is very limited and it is seldom used for voltages over 15,000.

MODERN UNDERGROUND SYSTEM DESIGN

American practice generally has favored the "drawn-in" type of system in which cables are installed in one or more conduits which are buried in a trench, with manholes provided at intervals determined usually by the practical pulling lengths. European practice on the other hand has traditionally favored burying suitably armored cables directly in earth, without the use of conduit. Direct burial in this country has been limited essentially to street lighting, customers' service and local distribution cable circuits in parkways and residential areas where relatively unencumbered surface conditions permit sufficient access for maintenance without need for additional investment in conduits. Where there are numerous cables in a given trench, a properly designed drawn-in system affords a measure of protection against communicating faults between cables and against mechanical damage by hand excavating tools.

Natural exposures of underground cable installations to corrosive attack, damp environment and the risk of mechanical damage require that these factors be taken into account. The present extensive use of heavy-duty excavating tools and equipment, however, has greatly reduced the protection against mechanical damage previously afforded by conduit structures. Protection against corrosive environments is achieved by choosing cable constructions which avoid the use of metallic sheaths, or provide a protective covering over any metal which is required. Cathodic protection for pipe and metallic sheaths may be necessary in case of failure of the coating, but has to be carefully engineered because of its possible effects upon the corrosion of neighboring structures.

The increased use of pipe-type cable systems in this country has led to an intensive re-examination of the heat dissipating characteristics of earth. This in turn has led to a better understanding of heat dissipation from cables in other drawn-in and buried systems as well. It is already known that some grades of sand have extremely favorable heat dissipating characteristics and can be used to advantage as backfill when circumstances require. Earth is a very poor heat dissipating medium, so that cable losses in the order of 30 w per trench ft are about the maximum that can be permitted without risk of overheating, particularly at high load factors. For this reason conductor sizes are much larger for underground than overhead circuits having identical load ratings.

It is expected that research now under way will lead to a better understanding of these problems and some practical increases in load ratings. Where other things are equal, however, the superior heat dissipating properties of the atmosphere above the earth strongly favor the overhead installation of suitably modified cables. In the last analysis, the conductor and dielectric components of a cable are unaffected by considerations of whether the cable will be installed in underground conduit, buried directly in earth or installed overhead. The intended environment determines only the nature of the protection needed to preserve the insulating properties of the dielectric components. Armor of some sort may be added, particularly in submarine cables, to afford some additional measure of protection against mechanical damage.

Cables, however, represent only the conductor component of the underground distribution system which includes transformers, sectionalizing and protective equipment and numerous accessories. Because of the very high load densities which usually characterize underground distribution areas, the underground system generally takes the form of a low-voltage network supplied through transformers connected to diverse feeders which operate electrically in parallel through the low-voltage network in such a way that the outage of a feeder simply results in a redistribution of load between the feeders remaining in service, without resulting in any interruption of service to consumers.

In American practice, the distinction between network and radial circuits is used primarily to differentiate between those circuits which do and those which do not operate electrically interconnected. In common parlance, however, the term "network" almost universally applies to a system of interconnected low-voltage circuits, as in the 120/208-v systems most commonly used for combined light and power distribution. The networking of circuits involves considerations of normal and emergency load division, fault clearing, etc., which require the provision of additional facilities and techniques, but in all other respects the problems are quite similar for both network and radial systems.

The first low-voltage a-c network is reported to have been installed in Memphis about 1907. Its solid grid of secondary mains was supplied by primary feeders through primary cutouts and transformer banks which were connected to the grid through fuses. In 1921 an improvement was made by the Puget Sound Power Co. in Seattle, when the first use was made of reverse-power tripped, manually reclosed, low-voltage circuit breakers for the isolation of network transformer or primary faults.

Further improvement was incorporated in the low-voltage a-c network system which was installed in New York City by the United Electric Light & Power Co. in 1922. In this system a number of radial primary feeders supplied a solid grid of low-voltage mains, with the transformers connected to the grid through network protectors. Transformer or primary faults are cleared by reverse-power tripping of the network protector breakers, so as to disconnect from the network all transformers being supplied by the feeder associated with the fault. The network protector breakers automatically remain open until the necessary repairs have been completed and the primary feeder is re-energized, whereupon service is restored by automatic reclosing of the network protector breakers. The first use of supply feeders at 13-kv generator voltage for such a network was made in New Orleans in 1923.

By 1926 another type of network system had been developed and installed in Philadelphia, in which sectionalized primary feeder loops were used instead of radial feeders. A transformer or primary fault in this system causes current unbalance in a differential protection control circuit which automatically opens the immediately adjacent primary circuit sectionalizing breakers and isolation of the fault is completed by the operation of fuses in the low-voltage leads of the one transformer affected, thus making it unnecessary to provide for any automatic reclosing features.

Acceptance of a-c network systems was initially characterized by caution, as certain weaknesses became apparent and were being eliminated. Nevertheless, there were six of these networks operating with a total load of 27,500 kva in 1925, when the 120/208-v 3-phase system for supplying combined light and power service had become generally accepted. Increased confidence led to rapid growth thereafter, so that some 52 companies operated 152 networks having a total load of 783,000 kva in 1931, when the first edition of this book was published. By 1952 eighty-two companies operated 414 networks covering nearly 150 miles of area and having a total load of about 4,500,000 kva. During the development of the network systems, the secondary voltages in some instances have been increased to 265/460 v and the primary supply voltage as high as 39,000 in order to economically provide for load demands.

With increasing load density, maximum network transformer sizes have increased from 100 kva for single-phase units of the early networks to 1000-kva 3-phase units for present 120/208-v systems and 2000-kva 3-phase units for 265/460-v service. Modern transformers are physically smaller than predecessors of equal rating, which is important because increasing subsurface congestion requires developing the most compact designs practical. Vaults under sidewalks are generally preferred, with a maximum of free area provided for venting their losses to outside atmosphere.

Important space-saving features have included the elimination of external cooling tubes from the transformer and mounting the network protector with other accessory equipment on the transformer tank in a package requiring a minimum number of cable connections conveniently located on top. Recent development of suspension-type mountings also holds promise of appreciable construction and maintenance economies by reducing the vault size and avoiding the more corrosive environment near manhole floors. The use of all-welded construction and solder-sealed bushings to eliminate any need for gaskets has considerably simplified maintenance. Askarel-filled and dry types of transformers are available when desired to avoid the use of oil-filled units in buildings. Transformer noise level is important in residential areas and should be kept within acceptable limits.

The modern network protector and associated protection facilities have undergone many changes in mechanical detail, but the basic requirements have remained unchanged since 1922. Back-up protection against failure of the protector to open is now provided by fuses coordinated with limiters in the cable connections to the street mains or network bus. The limiters are designed to coordinate with the load-temperature-time curves of the cables which they respectively protect against damage that might otherwise result from sustained secondary faults. The need for an adequate fault return path requires special consideration which has been emphasized by the trend toward a greater use of nonleaded cable. The use of precast manholes, vaults, etc., has permitted substantial construction economies in some areas by expediting field work and has reduced street traffic inconveniences.

There are many things which need to be considered in the design of a modern underground network system, a number of which apply with equal force to radial systems as well. The mains, transformers and feeder systems must have adequate capacity to supply the load under both normal and emergency conditions. A usual minimum requirement is that provisions be made for having one of the feeders out of service at any time without risk of low voltage or excessive overload. In some cases, particularly in important network areas, sufficient flexibility must be provided so that the foregoing requirement is satisfied for the remaining feeders when one of the feeders is out of service for scheduled work. Feeder layouts, therefore, should provide for a diversity of loads, feeder supply buses and routes, to minimize distress associated with feeder or bus section outages, or loss of all feeders in a common cable route. Also, the station design should be such as to prevent the phase angle between network feeder supply buses from exceeding tolerable limits.

Network designs should also include provisions for a complete shut-down in the event of major system trouble and for restarting afterward, without damage to the system. In general, this requires provisions for re-energizing most of the feeders involved simultaneously in order to avoid possible extensive and annoying overload operations of network protector fuses and limiters. The total load in a given network, therefore, should not exceed a value which can be successfully restarted.

TREND TO HIGHER VOLTAGES

The nature of the power distribution system is such that the kva of load which can be distributed from a given distribution center depends upon a number of pertinent factors. Among these is the fact that the number of underground cable circuits which can be routed to and from a given substation site usually limits the maximum coincident load which can be distributed from that site to a value in the order of 5000 to 10,000 amp, per phase, at any voltage. Hence, the pressure for efficient load distribution at the continually increasing load densities has been accompanied naturally by a trend toward higher distribution voltages. This has been accomplished primarily by superimposing higher voltage supply circuits on existing systems, but also in part by increasing the voltage levels of circuits which supply distribution transformers.

When one considers that the term "distribution system" in its broader sense includes all of the circuits operating at the various voltage levels as necessary to connect the power sources and the consumers' meters, it will be understood that the trend toward higher voltages applies with equal emphasis to so-called "subtransmission" and "transmission" circuits and is naturally related to the accompanying trend toward larger unit sizes of transformers, generators, etc.

The corollary effect upon underground cable systems has been one of increasing pressure for higher load ratings which has been met in part by increasing conductor sizes to the extent permitted by practical conduit sizes and a-c loss considerations, but principally by resort to the use of higher voltage circuits. Generator sizes already exceed the 200,000 kva maximum practical load rating of present underground cable circuits. Overhead rights-of-way are becoming increasingly difficult to obtain. Such has been the path of progress from Edison's day when his 250-kva, 1000-amp circuit was altogether sufficient.

CONDUCTORS

Economics largely determine the selection of conductor material, taking into consideration initial and operating costs, salvage value, availability, conduit occupancy, jointing and terminating facilities and, in some applications, physical and chemical properties.

Annealed copper generally has continued to be used for insulated wires and cables because of its high conductivity, ready workability and ease of handling. Considerations of availability and cost have led to increased use of aluminum where the larger conductor size is not a handicap. For comparable load ratings up to 2/0 AWG copper size, aluminum conductors are two AWG sizes larger and above 2/0 equivalent have correspondingly greater cross-sectional area.

The resistance of a conductor is greater when carrying alternating than direct current because of skin, proximity and magnetic effects (see Chapter 2). A-c/d-c resistance ratios have been established for various conductor constructions in single- and multi-conductor cables installed in both magnetic and nonmagnetic environments.

To reduce the a-c resistance of large size (1000 MCM and larger) single-conductor cables, it is common practice to use segmental conductors, a development which practically has replaced annular conductors. However, this conservation of space is obtained at some sacrifice of current-carrying capacity, since cables having the smaller diameter segmental conductors have slightly less heat dissipating capacity.

The flexibility of a concentrically stranded conductor generally is dependent upon the number of component wires, although this effect is largely masked by the stiffness of the associated cable insulation and sheaths. Ordinarily, ASTM Classes B, C and D are used for insulated conductors. For effective use of limited conduit sizes, however, practically all 4/0 AWG and larger 3- and 4-conductor solid-type paper-lead cables are manufactured with less flexible compact sector conductors.

CABLE INSULATION

World War II led to the production of several types of synthetic rubber-like materials which, either because of their specific properties, availability or economy, have largely replaced natural rubber for insulating compounds. These are known as Buna-N or GR-S, Butyl rubber or GR-I and Neoprene or GR-M, the last being in extensive use for outside jackets of cables. GR-S and natural rubber with mineral fillers are used for low-voltage cables and, with vulcanized vegetable oil, for higher voltages. Butyl rubber, with mineral fillers, is a more recent development which, like the oil-base compounds, is commonly used for voltages up to 15,000, although some cables of both types are operating at 25,000 v.

Two types of thermoplastic insulations are used for power wires and cables, the vinyls and polyethylene. There are several polyvinyl chloride compounds, generally known as PVC, the first of which appeared in 1935, which differ in behavior at high and low temperatures and in other characteristics. Polyethylene, which was introduced during World War II, has excellent electrical properties, the lowest moisture absorption and best low temperature flexibility of any of the insulations available for power cables. It suffers from a rather low softening point and susceptibility to ionization if not carefully shielded. It is used for aerial, underground and submarine cables up to 15,000 v.

Except for a small increase in its permissible operating temperature, varnished-cambric insulation has not greatly improved in recent years. For high temperature work, especially in power stations, it is being displaced by insulation composed of glass fabric filled with either silicone rubber or a silicone resin.

Impregnated paper remains the principal cable insulation for voltages above 5000. The type commonly used for voltages up to 15,000, and occasionally up to 35,000, is the so-called "Solid Type" which has a viscous impregnant and is usually sheathed in lead; but aluminum sheaths are now used to some extent. Oil-filled cable of the original low-pressure Pirelli type provided a means for accommodating thermal expansion effects which has earned it a reputation for reliability at voltages from 69,000 to 138,000 v, and is entirely practical for 230,000 v. By applying a pressure of 100 psi and reinforcing the sheath, the voltage limit of oil-filled cable has been raised to 425,000 for very short lengths of cable in vertical shafts, as used in Sweden. At the higher voltages some useful gain in electric strength has been effected by using thinner tapes near the conductor. Two similar types of impregnated-paper-insulated cables using the pressure principle are the low- and medium-pressure gas-filled cables in which surplus oil has been drained out and replaced by nitrogen gas under a pressure of 15 psi for voltages up to 46,000 and under a pressure of 40 psi for voltages up to 69,000. In the latter case, lead sheaths have to be either reinforced or replaced by aluminum sheaths.

The majority of recent cables for voltages from 69,000 to 230,000, in America, have been of the "Pipe Type" in which three paper-insulated single-conductor cables are placed in a steel pipe with either oil or nitrogen gas as the pressure medium at 200 psi. There are four types, in two of which the insulation is pervious to the pressure medium, be it oil or gas, and two in which the insulation is made either wholly or partially impervious by providing the cables with polyethylene sheaths.

For the future, there must be advances in the reduction of dielectric loss, reduction of charging current, improvement of dielectric strength and improved heat dissipation in order that long extra-high-voltage underground cables may have the carrying capacity required.

CABLE SHEATHS AND COVERINGS

The developments which have taken place during the past 25 years in the protective coverings over insulation, although not as spectacular as the improvements in insulation, have, nevertheless, contributed to the successful transmission and distribution of power. Utility engineers have paid careful attention to the operation of power cables by making a detailed analysis promptly to determine the cause of each failure. The failure may be due to such causes as deterioration of the insulation by overheating, deterioration of the covering (such as a braid) and corrosion, abrasion, splitting or fatigue of the lead sheath.

The resulting better knowledge of cable operation has led to improvements in the types of coverings. For example, in the 1920's a saturated cotton braid over rubber insulation was the usual practice. In dry locations this is a satisfactory protective covering, but in wet locations it will be completely destroyed within a few years. About 1940, braids were supplanted by neoprene coverings, which are giving satisfactory operation for rubber-insulated cables in ducts and wet locations. Also, they are highly resistant to sunlight and weather, as well as chemicals likely to be encountered in service. Thermoplastic coverings, such as polyvinyl chloride and polyethylene have also come into usage in place of fibrous braid coverings to provide a more permanent protective covering for insulation.

Experience with commercial lead sheathing has shown that cable movement in ducts and manholes, caused by cyclic temperature changes, may in some situations result in early intercrystalline fatigue cracks in the sheath. Certain alloys of lead containing arsenic have superior bending fatigue resistance. Tellurium is also being used in addition to arsenic. Investigations of permissible cyclic strains have established criteria for manholes and cable training, which also have permitted obtaining greatly increased sheath life where thermal movement is a limiting factor.

A recent improvement in manufacturing processes is the elimination of press-stops by the use of the continuous lead press which extrudes commercial lead in any desired length.

Aluminum sheathing has considerable promise for the future, but problems of manufacture and jointing severely limit present use. The high strength and creep resistance of aluminum as compared to lead should favor its use for oil-filled or gas-filled cables having high internal pressures. Laboratory tests have indicated that the bending fatigue resistance of presently available aluminum sheaths is essentially the same as that of alloyed lead sheaths at cyclic strains not in excess of 0.15 per cent. The specific gravity of aluminum is about 23 per cent of that of lead and should be very helpful in reducing the weight of cables. Adequate corrosion protection for underground installations, however, requires the use of some covering, such as neoprene or polyethylene.

Due to its higher electrical conductivity the losses in aluminum sheaths are higher than for lead sheaths and result in a higher a-c/d-c resistance ratio. Both of these factors result in some reduction in the current-carrying capacity. Bright aluminum surfaces have lower emissivity than lead, but the effect is of minor importance because it vanishes when protective coverings are used and probably is offset by weathering in other cases.

There have been no changes in the flat-tape or round-wire types of cable armor, except that there have been a few cases where aluminum wire armor has been used to reduce the sheath losses of single-conductor submarine cables.

For industrial plant installations, the use of interlocked cable armor is gaining favor over previous drawn-in installations.

The corrosion of lead sheaths in ducts has become quite an important cause of cable failures. This is due in many cases to the abandonment of electric trolley systems, which previously afforded a measure of cathodic protection. Certain soil waters are also detrimental to lead. The use of neoprene and polyethylene coverings over the lead sheath has been quite successful in such exposures.

Since pipe-type cable systems are buried directly in the ground, the steel is subject to corrosion unless protected, usually with an asphalt-mastic covering compound of sand, asphalt and asbestos. Asphalt and coal-tar enamels wrapped with inorganic materials have also been used.

CABLE TESTING

The past 25 years have been noted for the greater attention paid to the testing of the material entering into cables used in the electric power industry, the finished product and later during its operation. Specifications are now available which cover acceptance tests pertaining to both the physical and electrical properties of a cable. These include requirements for dimensions and materials, factory accept-ance tests, design tests, accelerated aging tests as well as tests on installation and during its life.

At the cable manufacturer's plant there are the usual routine tests for conductor resistance, insulation resistance and proof voltage on each shipping length of cable. In addition, there are specific tests applicable to each type of insulation. For example, for rubber-insulated cables, the insulation is tested for its physical properties, i.e., tensile strength, elongation and heat-aging characteristics. For high-voltage rubber cables, the insulation is checked for its ozone-resistant properties and for exposure to corona discharges. Moisture absorption of rubber is an important factor, so there are tests to determine the amount of water that may be absorbed gravimetrically or its effect on the dielectric constant and power factor.

Impregnated-paper-insulated cables are given a careful inspection of the quality of manufacture as indicated in the uniformity of taping, freedom from wrinkles and large gap spaces, the degree of saturation and the firmness of the insulation. Every shipping reel length for cables rated 8 kv and over is given an ionization test and a sample is required to pass a high-voltage test for at least six hours. Dielectric loss power factor versus temperature tests are required on some samples.

The coverings of the insulation are also tested for such properties as: for braids, their uniformity of weave, degree of saturation, flame resistance and moisture resistance; for lead sheath, its chemical composition, bending to fracture and tensile strength and elongation; for jackets, such as neoprene and polyethylene, their physical properties, aging under heat and resistance to fluids.

Although a-c voltages are normally used in the testing of cables in the factory, many cable manufacturers of rubber-insulated cables, in addition, will test their cables after the a-c voltage test with d-c voltage at values up to three times the a-c voltage as a further check to eliminate any weak spots in the insulation. Another test on rubber-insulated cables now being given considerable attention is a corona-voltage test to pick out voids in the insulation.

Utilities are requesting longer shipping lengths of cable in order to reduce the number of manholes, which are costly. Greater interest is being shown in submarine crossings, so we find the cable manufacturers equipping themselves to handle very long lengths, as high as 25,000 ft of cable in one length. High kva test set capacities are required for a-c voltage testing of these cables because of the high charging current, although this requirement can be reduced by the use of suitable shunt reactors.

Field testing has greatly increased and broadened in the past 25 years as a further aid to improving service. Voltage acceptance tests, mostly with d-c voltages, have become standard with periodic testing from time to time by many utilities. Better knowledge of the extent of corrosion and its effects has emphasized the need for electrolysis surveys of drawn-in and buried cables. Such surveys are now commonly used to determine what is the best method for mitigating the corrosion. Methods for fault location on cables include the use of d-c voltages, 60-cycle power, audio frequency and impulse charges on the cable. Methods also have been developed to check the efficacy of the coverings over pipes at the time of installation and later during operation.

STANDARDS AND SPECIFICATIONS

Except for underground transformers, cables and cable accessories, no industry specifications have been published for other components of an underground system, such as cutouts, disconnects, oil switches, network protectors, cable racks and oil reservoirs. Some of the large users of this equipment, however, have their own specifications. There has been considerable progress, however, since the 1931 edition of this book, which noted in its Introduction, "There is a rather surprising lack of standardization in many phases of underground practice. The thickness of insulation to be used for any type of cable, . . . and many other important questions are still matters of opinion, and may vary between wide limits."

When one considers the number of national organizations which have been actively working in this field during the past 25 years, it is understandable that the newcomer may be bewildered by the many governing standards and specifications which have been developed for various items comprising the underground distribution system and related engineering practices. The organizations presently engaged in standardization work are:

AEIC ...	Association of Edison Illuminating Companies
AIEE ...	American Institute of Electrical Engineers
ASA	American Standards Association, Inc.
ASTM ..	American Society for Testing Materials
CAA	Civil Aeronautics Administration, Department of Commerce
EEI	Edison Electric Institute
IMSA ...	International Municipal Signal Association, Inc.
IPCEA ..	Insulated Power Cable Engineers Association
NEMA ..	National Electrical Manufacturers Association
UL	Underwriters Laboratories, Inc.

These organizations publish numerous standards and specifications for the design, manufacture, testing and application of many components of an underground system. Recommended engineering practices also are available. For reference, Table I presents a summary of the items for which standards are now available, together with the identity of the one or more organizations publishing some standard affecting the item.

For solid-type paper cable, the first specifications were prepared by a Joint Subcommittee of the Underground Systems Committee, NELA, and the Transmission and Distribution Committee, AIEE, "in Conference with Representatives of (9) American Manufacturers of Paper-Insulated Lead-Covered Cable." They were published in the 1920 Report of the Underground Systems Committee (NELA Publication T4-20); revised in April, 1927 (NELA Publication No. 267-25); and withdrawn by the Committee on January 22, 1930, in favor of the specifications prepared by AEIC.

The first AEIC specifications were prepared "under the auspices of the Lamp Committee in cooperation with the Electrical Testing Laboratories and representatives of (7) Operating Companies and (5) Manufacturers." They were printed on November 1, 1924, and were revised in 1926, 1928, 1930, 1931, 1934, 1937, 1939, 1945, 1946 and 1949, with the 9th and most recent edition having been published in April, 1954.

A "Simplified Practice Schedule," developed in July, 1941, was a heroic but ill-fated attempt to achieve the ultimate in standardization by the publication of a schedule of a limited number of conductor sizes and voltage ratings with related insulation thickness. It was adopted by only a few members of AEIC.

For oil-filled cable, the first specifications were prepared by the High-Tension Cable Committee, AEIC, in consultation with four cable manufacturers and issued as "Appendix A," dated September, 1931, to the 4th (July, 1930) edition of the specifications for solid-type cable. These were revised in 1934, 1938, 1939, 1945, 1946 and in 1951 when the current 5th edition was issued.

For low-pressure gas-filled cable, the first specifications, prepared by the Power Distribution Committee, AEIC, were printed in January, 1948, and are currently effective.

The first and presently effective specifications for high-pressure pipe-type cable were prepared by the Power Distribution Committee, AEIC, in consultation with manufacturers of such cables and printed in September, 1951.

TABLE I—PUBLISHED STANDARDS AND SPECIFICATIONS

Items	Sponsors
Conductors, prior to insulating	ASA, ASTM
Rubber- and thermoplastic-insulated cables	ASA, ASTM, IPCEA, UL
Varnished-cambric-insulated cables	ASA, IPCEA, NEMA, UL
Asbestos-insulated cables	ASA, IPCEA, NEMA, UL
Paper-insulated cables (solid, oil-filled, pipe)	AEIC, ASA
Service cables	UL
Signal cables	IMSA, IPCEA
Airport lighting cables	CAA
Metallic coverings for insulated cables	ASA, IPCEA
Nonmetallic sheaths for insulated cables	ASTM, IPCEA, UL
Lead, for sheathing	ASTM
Steel wire and tape, for armoring	ASA, ASTM, IPCEA
Cable-reel dimensions and capacities	IPCEA
Connectors	EEI, UL
Wiping solder	ASTM
Filling and treating compounds (testing)	ASTM
Potheads (electrical requirements)	AIEE
Limiters (under preparation)	AIEE
Transformers	EEI, NEMA
Definitions and general standards	AIEE, ASA
Recommended shielding practice	AEIC, IPCEA
Color code for control cable	IPCEA, NEMA, UL
Test voltages for insulated cables (factory, installation acceptance and proof, service proof)	AEIC, ASTM, IPCEA, UL
Recommended pulling tensions for leaded cables	IPCEA
Minimum bending radii for permanent installation	IPCEA
Current-carrying capacities of insulated cables	IPCEA, NEC*
A-c/d-c resistance ratios	IPCEA
Relation between load and loss factors	NELA**
Thermal resistivities of insulations and coverings	IPCEA, NEMA
Emissivities of protective coverings	NEMA
Thermal resistance of conduit	IPCEA
Conduit group factors for horizontal and vertical banks	IPCEA

*NEC—National Electrical Code
**NELA—National Electric Light Association

OPERATION

Improvements in manufacturing techniques and quality control have now reached the point where operating troubles due to initially defective cable have been reduced to a level which now represents less than 2 per cent of the over-all trouble rates for cable and joints. Mechanical damage and joint troubles are almost equal contributors to 60 per cent of all cable and joint troubles and it is thought that perhaps one-half of these are related to the movement or strain associated with cyclic loads and temperatures. Lead sheath corrosion accounts for an additional 17 per cent of the troubles. It is thus seen that more than three-quarters of all cable operating troubles are attributable to mechanical damage, jointing and corrosion problems such as are primarily associated with the engineering and construction techniques employed in making each particular installation.

Two valuable statistical reports having to do with underground operations have been published for a number of years and include much useful reference data. The EEI-AEIC series of Annual Reports entitled "Cable Operation," include a detailed analysis of the performance of paper-lead cable and accessories operating at voltages above 7500 v, in systems having 200 miles or more of such cable. The triennial series of EEI Transmission and Distribution Committee reports entitled "A-C Network Operations" give comparable information concerning the operation of underground network systems.

Techniques which have been proved by years of experience in the construction, operation and maintenance of underground systems are carefully presented in this new *Underground Systems Reference Book*, including among other things much useful material concerning loading, corrosion, field testing, safety procedures, etc. If on occasion the reader is tempted to conclude that some details are unessential, he should promptly remind himself that a little extra thoroughness now can avoid a lot of future grief. Perhaps the most important general conclusion which has been reached by those familiar with underground systems is that the only effective way to avoid future operating problems lies in the consistent exercise of persistence in giving careful attention to details even though some of them may seem unimportant to the uninitiated.

TABLE OF CONTENTS

An alphabetical index appears after Chapter 15.

CHAPTER 10—CABLE AND UNDERGROUND EQUIPMENT LOADING

CHAPTER 11—CABLE TESTING, FAULT LOCATION AND CABLE IDENTIFICATION

PAGE

CHAPTER 12—RECORDS, REPAIRS AND MAINTENANCE

CHAPTER 13—CABLE AND EQUIPMENT RECONDITIONING

CHAPTER 14—CORROSION

CHAPTER 15—SAFETY PRACTICES

LIST OF TABLES