Fiber Optic Cables in Overhead Transmission Corridors

A State-of-the-Art Review

TR-108959

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REPORT SUMMARY

Many electric utilities are installing high capacity fiber optic cables and wires on their high voltage lines to satisfy their own internal communication needs and to gain additional revenues by leasing excess capacity to telecommunication network providers. This report presents a review and evaluation of the state-of-the-art in using fiber optic technology in high voltage corridors.

Background

Within the power utility industry, reliable internal communications are vital to ensure protection and control of the power system. With the advent of digital fault protection systems, integrated power system automation signal densities are increasing; and fiber optics can offer a unique solution to the ever increasing demand for bandwidth because of its remarkably high capacity for carrying data -- single pair of fibers can carry nearly 8000 simultaneous voice channels. The immunity of fiber optics to electromagnetic interference is another advantage. However, integrating fiber optic cables into high-voltage corridors also poses some technical and safety-related challenges.

Objectives

- To identify and evaluate relevant technical information on using fiber optic cables in high voltage corridors.
- To summarize currently available technical information, applicable regulatory codes and standards, state of practice of industry leaders, and current information and technology gaps.

Approach

The project team conducted an exhaustive literature review on the integration of optic technology into overhead power transmission lines. They summarized the state of practice of fiber optic cables integration in high voltage corridors in the United States power industry, including regulatory considerations, product descriptions, electrical and mechanical factors, and issues related to installation, inspection, and maintenance.

Results

In current practice, three different cable options are available to an electric utility that elects to integrate communications into an existing power transmission system. Optical fibers can be:

- Encased within the ground wire (OPGW)
- Wrapped around the phase conductor or the ground wire (WRAP)
- Contained in an all-dielectric-self-supporting cable (ADSS)

For each option, the report gives typical material and installation costs for aerial cable or wire with either 24 or 48 optical fibers. The cost of the cable/wire itself and the labor required in the installation make up the majority of the system development cost.

The relatively new practice of integrating fiber optic cables into high voltage corridors poses some technical and safety-related challenges. For example, since ADSS and WRAP type fiber optic cables are located in high electric fields, there is a the threat of sheath damage and cable failure similar to the aging of non-ceramic insulators. Also, the high working tensions necessary for adequate ground clearance exposes the light-weight OPGW and self-supporting ADSS fiber optic cables to wind-induced vibrations that can damage the cable and attachment hardware. The report summarizes current experience with these and related problems and identifies technological issues that remain to be addressed. The report includes an exhaustive set of references to the technical literature.

EPRI Perspective

Besides providing a comprehensive introduction to the state of practice of integrating fiber cable technology into high voltage transmission corridors, this report can be used by EPRI members to identify subject areas and technological issues that need to be addressed.

TR-108959

Interest Categories

Overhead construction, O&M
Overhead planning, analysis & design

Key Words

Fiber optic
All-dielectric self-supporting (ADSS)
Optical ground wire (OPGW)
Wrap type cables(WRAP)
Transmission line

ABSTRACT

Overhead transmission power line corridors provide the telecommunications industry with cost-effective alternative routes and at the same time benefit the electric utilities by generating additional revenues using existing facilities. The inherent advantage of fiber optic technology as a means of communication is that fiber optics provide fixed link, point to point communications with a remarkably high capacity for carrying data. For example, a single pair of fibers can carry nearly 8000 simultaneous voice channels.

Currently, fiber optics can be integrated into an overhead power transmission line in four different ways. The optical fibers can be:

- Encased within the Ground Wire (OPGW)
- Encased within the Phase Conductor (OPPC)
- Wrapped around the Phase Conductor or the Ground Wire (WRAP)
- Contained in an All-Dielectric-Self-Supporting Cable (ADSS)

However, the practice of integrating fiber optic cables into high-voltage corridors also poses some technical and safety related challenges. Since ADSS and WRAP type fiber optic cables are located in high electric fields there is the threat of sheath damage and cable failure similar to the phenomena related to aging of non-ceramic insulators. Also, the high working tensions necessary for adequate ground clearance and minimum amounts of self-damping expose the light-weight OPGW and self supporting ADSS fiber optic cables to wind-induced vibration, which can damage the cables and hardware.

Addressing these and other relevant issues, the Electric Power Research Institute’s (EPRI) advisory committee on fiber optics in utility corridors decided that it would be beneficial to the member utilities to review and evaluate the current state-of-the-art. Results of this investigation are summarized in this report.

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INTRODUCTION

1.1 Background

Within the power utility industry, reliable internal communications are vital to ensure protection and control of the power system. Such communications traditionally have been provided by methods such as power line carrier and microwave radio systems but are more recently being supplemented or replaced by fiber optics. However, with the advent of digital fault protection systems, integrated power system automation signal densities are increasing and fiber optic communications can offer a unique solution to the ever increasing demand in the future. Consequently, many electric utilities are installing high capacity fiber optic cables and wires on their high voltage lines to satisfy their own internal communication needs and to gain additional revenues by providing excess capacity to telecommunication network providers.

Overhead transmission power line corridors provide the telecommunications industry with cost-effective alternative routes and at the same time benefit the electric utilities by generating additional revenues using existing facilities. The inherent advantage of fiber optic technology as a means of communication is that fiber optics provide fixed link, point to point communications with a remarkably high capacity for carrying data. For example, a single pair of fibers can carry nearly 8000 simultaneous voice channels.

The immunity of fiber optics to electromagnetic interference is another advantage for its use in power delivery systems as long as care is taken to shield any terminal and repeater stations. Typically, there are no radiation or frequency assignment difficulties as commonly experienced with power line carrier, intra-bundle, and microwave communication systems. Also, fiber optics increase the security of the transmission systems since the technology virtually eliminates the unauthorized monitoring of vital communications. Last, fiber optics do not require coupling devices or other specialized connectors and can be easily and cost-effectively integrated into any digital network.

Fiber optics can be currently integrated into an overhead power transmission line in four different ways. The optical fibers can be:

- Contained in an All-Dielectric-Self-Supporting Cable (ADSS)
- Encased within the Ground Wire (OPGW)

- Encased within the Phase Conductor (OPPC)
- Wrapped around the Phase Conductor or the Ground Wire (WRAP)

With the development of high strength-to-weight ratio insulating materials, ADSS cables are currently becoming available that are suitable for overhead power lines with span lengths of up to 1000 meter (3284 feet). In this embodiment, the ADSS cable is often capable of maintaining the same mid span clearance to ground as the conductor without tower reinforcement under governing wind and ice loading conditions. A major advantage of the ADSS system is that it can be regarded as separate from the power system and is therefore attractive to third party users such as telecommunication providers.

Currently, there are a number of OPGW wires available that can be directly integrated into existing transmission rights-of-way as replacements for traditional shield wires. OPGW wires typically have the correct combination of flexibility and strength to approximate the sag and tension characteristics of existing shield wire installations for most span lengths. Consequently, the ease of integration into existing rights-of-way makes this alternative to underbuild or wrapped cables very attractive to electric utilities.

OPPC fiber optic cables have not been used extensively by North American utilities but are in many ways very similar to OPGW fiber optic cables. Due to the difficulty associated with the replacement and/or upgrade of the phase conductor with the installed fiber optic cable (i.e., OPPC) the technology appears not to have gained a foothold in American utility companies. Consequently, the discussion of OPPC fiber optic cables has been excluded from this review.

WRAP fiber optic cables eliminate the need for specially shielded transition hardware and can typically be installed economically without requiring any structural modifications to the supports. Wind tunnel tests show that the wind load on the shield wire or conductor typically increases no more than 10 percent for most wrapped fiber optic cables resulting in little or no structural modifications. The ease of installation of relatively inexpensive fiber optic cable in a very short time frame makes this option attractive to telecommunication providers.

However, the relatively new practice of integrating fiber optic cables into high-voltage corridors also poses some technical and safety related challenges. Since ADSS and WRAP type fiber optic cables are located in high electric fields there is the threat of sheath damage and cable failure similar to phenomena related to aging of non-ceramic insulators. Also, the high working tensions necessary for adequate ground clearance expose the light-weight OPGW and self supporting ADSS fiber optic cables to wind-induced vibration, which can damage the cable and attachment hardware.

Addressing these and other relevant issues, the Electric Power Research Institute's (EPRI) advisory committee on fiber optics in utility corridors decided that it would be beneficial to the member utilities to review and evaluate the current state-of-the-art. Results of this investigation are summarized in this report.

1.2 Objectives

The goal of this report is to provide a critical and impartial review of the current state-of-the-art in using fiber optic technology in high voltage corridors. This document can be used by the EPRI target member advisors to identify subject areas and technological issues that need to be addressed. The main goals of this investigation are:

- Identify and evaluate relevant technical information on using fiber optic technology in high voltage corridors (establish State-of-the-Art) .
- Summarize currently available technical information, applicable regulatory codes and standards, state of practice of leaders in the industry, and current information and technology gaps.

1.3 Literature Review

A survey of existing information revealed that there are a large number of publications (i.e., more than 100) dealing with OPGW and ADSS fiber optic aerial cables and related technical matters, while there are only a few that deal exclusively with WRAP installations. Most of the reference material that is relevant to the installation of fiber optic cables in transmission corridors addresses cable construction, cable testing, connection splicing, aeolian vibration, tracking, and dry band arcing. References are presented in Section 4 of this report.

Table 1-1 shows a summary of the 123 references sorted with respect to different aspects of fiber optic technology. The table differentiates between general, electrical, mechanical, and operational categories. These categories are subdivided further to distinguish between guidelines, regulatory codes, and manufacturer issues in the general category; the ADSS, OPGW, and WRAP type fiber optic cables and wires in the electrical and mechanical category; and installation, and inspection and maintenance oriented information in the operational category. However, many of the references and publications address multiple aspects of the technology and are listed in each applicable category.

Table 1-1
Referenced Technical Publications

		Applicable References & Publications **(See Section 4)**
General	**Guidelines**	1
	Regulatory	2, 3
	Manufacturers	4, 5
Electrical	**ADSS**	6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29 30, 31, 32, 33
	OPGW	6, 7, 8, 9, 10, 14, 15, 16, 17, 18, 20, 21, 22, 23, 26, 30, 34, 35, 36, 37, 38, 39, 40, 41 42, 43
	WRAP	6, 7, 8, 9, 10, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 30, 32, 33 44, 45, 46, 47
Mechanical	**ADSS**	7, 18, 20, 21, 22, 23, 28, 31, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63 64, 65, 66, 67, 68, 69, 70, 71
	OPGW	7, 18, 20, 21, 22, 23, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 48, 49, 50, 52, 53, 54, 55, 56 57, 58, 59, 60, 61, 62, 63, 64, 72, 73, 74, 75, 76, 77, 78, 79
	WRAP	7, 18, 20, 21, 22, 23, 44, 45, 46, 47, 48, 49, 50, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62 63, 64, 68, 70, 80, 81
Operation	**Installation**	7, 20, 22, 23, 25, 49, 60, 61, 64, 73, 79, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94 95, 96, 97, 98, 99
	Inspection & Maintenance	18, 37, 100, 101, 102, 103, 104, 105, 106, 107, 109, 110, 111, 112, 113, 114, 115 116, 117, 118, 119, 120, 121, 122, 123

Rather than summarizing and discussing the information documented in each publication in detail, it was deemed more beneficial to provide a short description to highlight the pertinent information contained in the referenced publications. These descriptions are provided in the following sections.

1.3.1 General

In the process of optimizing the construction, installation, and operation of ADSS, OPGW, and WRAP fiber optic cables it is important to follow a continuous quality improvement loop (7, 9, 18). The quality improvement loop typically addresses the theoretical and practical requirements, general parameters of the cable design and the selection of materials, the process control used in the production, the verification tests to be performed in the laboratory prior to installation in the field, the monitoring of field installations during the installation process, and evaluation of the long term performance during the service life of the components.

A tensile force is present throughout the full service life of ADSS, OPGW, and WRAP aerial cables. This tensile force causes the cable to elongate which needs to be considered in each step of the cable selection, installation, and operation. The total elongation of an aerial cable is typically divided into three different parts:

- A constant elongation strongly influenced by the unit weight, span length, sag, and mechanical characteristics of the aerial fiber optic cable or wire.
- A variable elongation that depends on the environmental conditions at the time of measurement such as wind velocity, ice load, and temperature variations acting on the aerial fiber optic cable or wire.
- Creep of the strength members and/or strands of the aerial fiber optic cable or wire caused by long term presence of tensile loads.

To restrict the cable or wire elongation to an acceptable level during the service life of the component, a strength member system has to be used that exhibits a sufficiently high modulus of elasticity in combination with a low unit mass and a small outside diameter that is capable of housing a satisfactory number of optical fibers (2, 8). Additionally, a good cable or wire design eliminates any axial strains to the optical fibers for all loading conditions that the aerial cable or wire may experience. Most aerial cables and wires in the past have typically been designed by the manufacturer to optimize one or the other aspect resulting in somewhat standardized designs that are currently offered for use in high voltage corridors.

ADSS, OPGW, and WRAP aerial cables and wires are exposed to much more extreme temperature variations than any other non-aerial cable types, sometimes encountering temperature variations of up to 100°C (212°F). However, due to the low thermal expansion coefficients of cable and wire wrapping and filler material in combination with relatively high moduli of elasticity, the cable expansion is typically dominated by the characteristics of the strength member (i.e., steel, aluminum, or composite strands).

A completely different situation may exist for non-metallic cables during low temperature storage on drums. Some composite strength members are not capable of absorbing any axial compression forces. These composite strength members require that the static coefficient of friction within a length of cable be larger than the force arising from the differences in thermal potential. This will prevent the respective layers from sliding relative to each other. Table 1-2 shows coefficients of thermal expansion for materials commonly used in the construction of aerial fiber optic cables. Coefficients of thermal expansion are shown for the fiber reinforced glass (FRP), polyester, polyethylene (PE), aramide yarns, and high density polyethylene (HDPE).

Table 1-2
Thermal Expansion Coefficients (Reference 105)

cable element	material	thermal coefficient of expansion ($10^{-6}K^{-1}$)
central strength member	FRP	5.0
stranded tubes	Polyester	80
inner-sheath	PE	150
strength members	aramide yarns	-2.0
outer-sheath	HDPE	150

The life of optical fibers is determined by the mechanical stress level in the fiber and the amount of moisture (i.e., relative humidity) present at the surface of the fiber as shown in Figure 1-1. Consequently, ADSS, OPGW, and WRAP aerial cables are constructed to minimize the ingress of moisture and level of stress to reduce the rate of deterioration of the optical fibers. Typically, stresses are controlled through the use of stranded loose tubes that allow for a certain amount of free cable or wire elongation without elongation of the optical fibers, while moisture ingress is controlled through the presence of the inner and outer sheath (i.e., ADSS and WRAP) or by the tube (i.e., OPGW). Ideally, the bending radius for most optical fibers should never be less than approximately 60 mm (2.5 inches) to prevent stresses that would otherwise damage most optical fibers (i.e., bending radius of 85 mm (3.5 inches) for 1550 nm fiber). This minimum bending radius corresponds to a maximum stress of 0.075 Mpa (11psi).

Cable and wire cores are typically standardized to include specific numbers of tubes that each contain one or more optical fibers. Optical fibers used in past installations of aerial cables and wires have been either single-mode or multi-mode. However, completely custom made cables have been designed in the past by either the customer or manufacturer in accordance with mechanical, electrical, and optical specifications most suitable to a particular transmission line application.

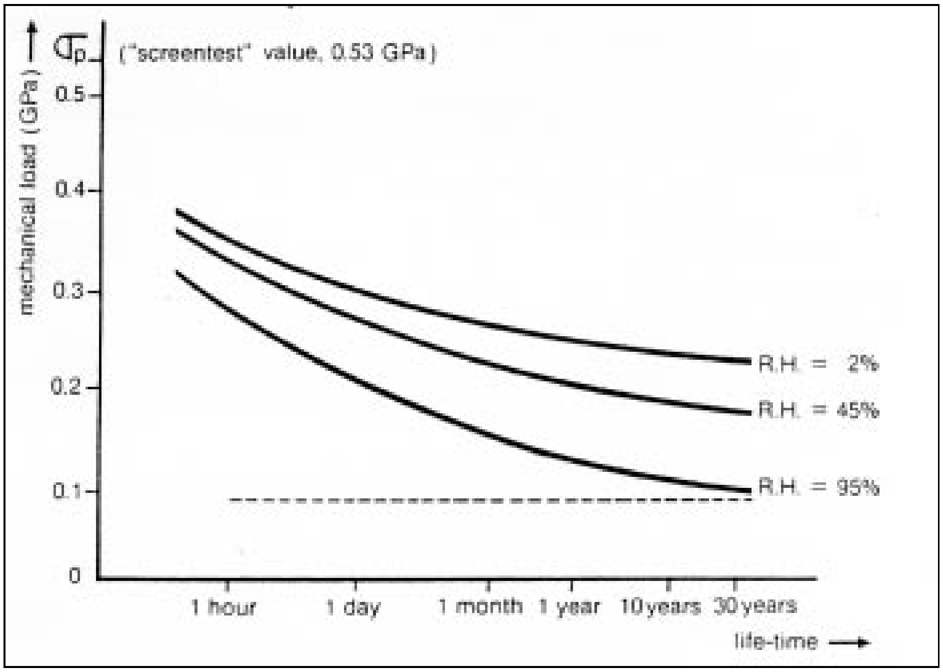

Figure 1-1
Correlation of Mechanical Load, Service Life, and Relative Humidity - Typical Optical Fiber (Note: 1Gpa = 145ksi, Reference 32)

It is important that the polyethylene enclosure (i.e., for ADSS and WRAP) or aluminum enclosure (i.e., for OPGW) of aerial fiber optic cables be resistant against weathering, UV radiation, acid rain, and the influence of electric fields. Additionally, the outer enclosure should have:

- High mechanical strength to guarantee excellent performance of the cable or wire when exposed to extreme loading conditions.
- Very low water permeability (i.e., low hydraulic conductivity).
- Adequate carbon black content to protect against thermal oxidation of ADSS and WRAP sheaths and corrosion resistance for OPGW tubes.
- High thermal stress cracking resistance to protect ADSS and WRAP aerial cables against thermal oxidation.
- High resistance against corona and tracking to protect ADSS and WRAP sheaths from the effects of high electric fields.

Tests are typically used to evaluate the electrical and mechanical performance of ADSS, OPGW, and WRAP aerial cables. These tests evaluate the tensile performance and ultimate strength of the cable or wire, the impact resistance of the construction, static and cyclic bending strength of the cable or wire, thermal cycling performance, resistance to water penetration, creep strain and rate, vibration self damping characteristics, vibration damper performance, resistance to shotgun damage, and lightning resistance. A more detailed description of the types of tests typically performed on ADSS, OPGW, and WRAP type aerial fiber optic cables and wires can be found in applicable Institute of Electrical and Electronics Engineers (IEEE) standards and specifications (1, 2, 3), as discussed in Section 2 of this report.

1.3.2 All-Dielectric Self-Supporting (ADSS) Cables

Typically, strength members of ADSS aerial cables are fabricated from high strength fiber glass filaments bonded in resin or Aramide yarn filaments. The effective elasticity modulus of high strength glass filaments bonded in resins (FRP) is about 50 kN/mm^2 ($7.25 \cdot 10^6$psi) with a specific mass of approximately 2000 kg/m^3 (125 lbs/ft^3). The stiffness and complete lack of relaxation of FRP strength elements permanently maintain bending and torsion stresses and make the material sensitive to fatigue and may, depending on the type of glass, be sensitive to moisture. Moisture sensitive strength elements are likely to loose integrity and strength within the fiberglass matrix.

The modulus of elasticity of Aramide yarn filaments used in ADSS aerial cables is approximately 100 kN/mm^2 ($14.5 \cdot 10^6$psi) for a specific mass density of only 1450 kg/m^3 (90 lbs/ft^3). Therefore, compared with the FRP strength member, the cable elongation, weight, and diameter of an ADSS aerial cable reinforced with Aramide yarn filaments are significantly lower.

Load-elongation relationships for ADSS cables are significantly different from comparable values for traditional ground wires and phase conductors since they vary substantially with the cable design. The difference between the free cable elongation and the cable elongation at maximum load should be at least 0.2 % (i.e., the length of the fibers should be at least 1.02 times the length of the tube), taking into account the long term creep of Aramide yarns, the variation in excess fiber length in the loose tube, and the initial cable elongation. An example of typical load-elongation test results as a function of span and sag is shown in Figure 1-2 for two different ADSS cables.

The selection of ADSS aerial cable materials should be performed on the basis of two main criteria: a) technical performance; b) long term stability and aging resistance. The technical performance of OPGW wires is very similar to the performance of similarly constructed ground wires and phase conductors, while the technical performance of ADSS aerial cables is strongly influenced by the type of materials used, the high and low temperature behavior, and the coefficient of thermal expansion of the cable.

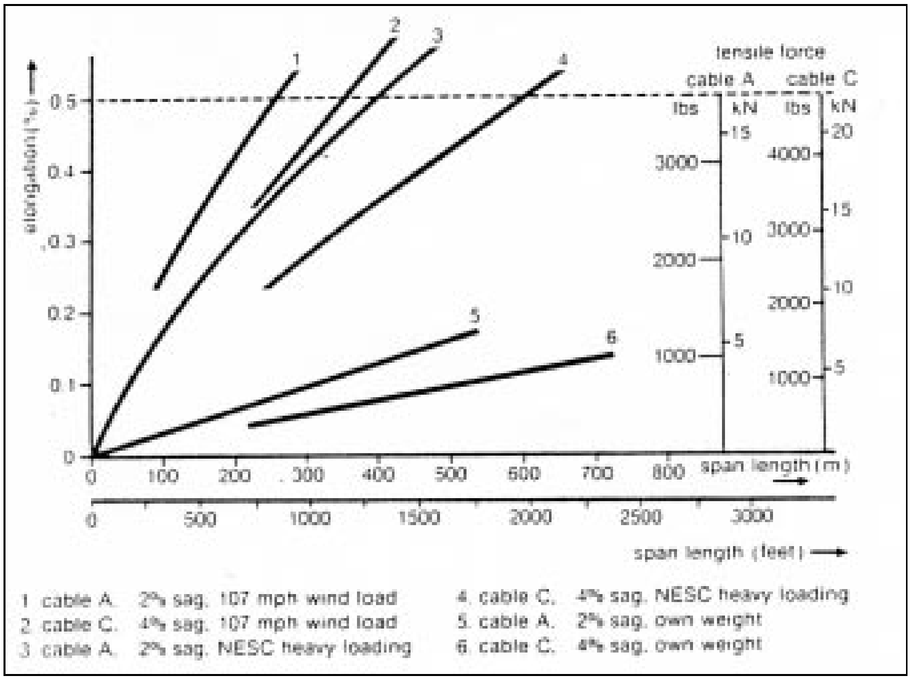

Figure 1-2
Typical ADSS Cable Load-Elongation Diagram (Reference 32)

Discharge mechanisms resulting from long term exposure to high electrical stresses contribute to the aging of the outer sheath on ADSS aerial cables. Generally, the two contributing mechanisms are caused by:

- Corona (i.e., luminous and audible partial discharges in a non-uniform electric field)

- Tracking or Dry-Banding (i.e., the process that produces localized deterioration and conducting paths as a result of the action of electric discharges on or close to the insulating surface)

Typically, the ADSS aerial cable is grounded at the suspension towers while it is charged by capacitive coupling in the middle of the span. As a result of the capacitive charge, the ADSS cable will have a potential that depends on the phase voltage and the position of the cable relative to the phase conductors and ground wire(s). Since the surface electrical resistivity of the ADSS aerial cable is very high, the outer insulation layer of the ADSS is not an equipotential surface and the resulting axial voltage gradients produce potential differences between the ADSS cable and the grounded hardware on the support structures.

The resulting electric field strength at the tips of the pre-formed attachment hardware is likely to produce corona (8, 9, 11) that may lead to failure of the ADSS aerial cable in a relatively short time period (i.e., observed time to failure ranges from two months to twelve months). This problem can be reduced significantly by the use of plastic attachment hardware instead of the traditional metal pre-formed hardware, but cannot be totally eliminated. Of course, the most effective way of avoiding excessive induced voltages is to place the ADSS cable in locations with a low electric field or low space potential. Typically, locations with field strengths not exceeding 15-25 kV/cm or a space potential of 15-20 kV are suitable for the installation of ADSS aerial cables.

Plastic spiral vibration dampers (SVD) must be installed at least 3 meters (10 feet) or more from the armor rod to prevent degradation of the components as a result of tracking. Ideally, spiral vibration dampers should be placed in electric fields not exceeding 2 kV/cm to minimize degradation of the components.

Also, whenever an ADSS aerial cable is polluted and wet, a low magnitude current is likely to flow from the middle of the span to the suspension tower (8, 9, 11, 13, 15, 16, 17). Wherever there are locations of higher current density caused by non-uniform pollution or wetting, local evaporation may take place due to current heating and dry bands are formed. The dry bands are stressed electrically to the point of breakdown and localized arcing occurs across the dry bands. The arcing can degrade the ADSS cable installation both, due to the energy involved in the arc and due to the chemical action of the arc products. This process can be continuous in some weather conditions and can cause the ADSS cable to fail in a relatively short time (i.e., observed time to failure ranges from two months to ten months).

1.3.3 Optical Ground Wire (OPGW)

Creep rates and strains for OPGW aerial cables are similar to values observed for phase conductors. Typical creep rates in percent elongation for different types of conductors are shown in Table 1-3. However, OPGW aerial cables are typically installed at an elevated tension to maintain NESC minimum clearance requirements on an existing right-of-way which may accelerate the rate of creep in the aluminum strands. At the same time, an increase in stringing tension will decrease the fatigue resistance and self-damping of the OPGW which in turn reduces the service life.

OPGW aerial cables are typically placed at the top of structures and thus experience lightning strikes and short-circuit currents. Core temperatures, under the passage of short circuit currents, can reach temperatures in excess of 100°C (212°F) which typically results in annealing of the aluminum components. It is important that there is no significant change in the optical attenuation of the optical fibers under these conditions.

Since the majority of these energy transients are caused by fault currents, it is necessary to take the maximum available fault current and the duration of the fault into account in the selection of the OPGW aerial wire. Consequently, it is important to correctly identify the fault level of the system to select the most suitable OPGW wire. OPGW aerial wires are typically rated using the maximum I^2t value. Also, it appears that the fault current testing stipulated in IEEE Standard 1138 is not representative of the use of OPGW aerial wires in the field. It can be argued that a full asymmetric fault lasting for 30 cycles is difficult to find at the average utility and almost impossible to produce under laboratory conditions. Our experience shows that faults are mostly symmetrical (i.e., if DC offset does occur it usually decays in 1 to 2 cycles). Consequently, as long as the I^2t rating is verified the shape of the simulated fault is unimportant.

Protection of the fibers against lightning strikes is provided by the outer layer of the OPGW or the metal layer of the fiber optic cable, which should be at least 2 mm (5/64 inch) thick. The fiber itself can tolerate very high temperatures, but thermal performance of plastic tubes, fiber coatings and aluminum or aluminum coated steel wires needs to be carefully considered.

Table 1-3
Conductor Creep Rates

	Typical Creep Rates of 795-kcmil Electrical Conductor					
	Tension @ 15% UTS			Tension @ 25% UTS		
	(10yrs) (%)	(20yrs) (%)	(30yrs) (%)	(10yrs) (%)	(20yrs) (%)	(30yrs) (%)
ACSR	0.050	0.056	0.060	0.097	0.109	0.116
AAAC	0.075	0.084	0.090	0.146	0.164	0.174
AAC	0.101	0.114	0.121	0.198	0.221	0.236
ACAR	0.081	0.091	0.097	0.158	0.177	0.189
AW	0.010	0.011	0.012	0.019	0.022	0.023
EHS	0.008	0.008	0.009	0.015	0.016	0.017
HS	0.009	0.010	0.011	0.017	0.020	0.021

Note: **Creep rates in percent elongation**

All creep rates derived for operation at room temperature (i.e., 68°F)

1.3.4 Wrap-Type Fiber Optic Cables (WRAP)

Similar to ADSS aerial cables, the selection of WRAP aerial cable materials should be performed on the basis of the same two main criteria: a) technical performance; b) long term stability and aging resistance. Since the WRAP type aerial cable is essentially an ADSS cable without a strength member (i.e., with the exception of the method of installation), many of the experiences with the ADSS cables apply also to WRAP type fiber optic cables. Consequently, the use of WRAP type fiber optic cables faces many of the same challenges of an ADSS installation.

The application of WRAP aerial cables is typically limited by the surface electric field gradients on the overhead ground wires as well as the conductors. In the past, installations of WRAP aerial cables were typically limited to applications on wires with surface gradients limited to less than 10 kV/cm. Typically, it is assumed that surface gradients in excess of 15 to 20 kV/cm significantly deteriorate the cable jacket as a result of surface corona and noticeably affect the economic life of the installation.

2

STATE OF PRACTICE

2.1 Regulatory Considerations

Standards are typically provided to assist both manufacturers and users of a specific technology in providing a common understanding of production and performance requirements. Standards applicable to the high-voltage transmission industry discussed in the following sections are the National Electrical Safety Code (NESC), the standards and guides developed by the Institute of Electrical and Electronics Engineers (IEEE), and the standards mandated by the International Electrotechnical Commission (IEC). It should be understood that there are also a number of other standardizing bodies involved in this particular technology that address subjects such as quality control and communication protocols. In addition, individual utilities and states develop their own regulations in certain areas of the industry. However, a discussion of these related standards is beyond the scope of this document.

2.1.1 Analysis and Design Guidelines

Currently there are no general analysis and design guidelines that specifically address ADSS, OPGW, and WRAP aerial fiber optic cables in high voltage corridors. However, there are a number of related American Society of Civil Engineers (ASCE) and IEEE guides and standards that address individual aspects such as the calculation of wind loads on the cable or wire, calculation of sags and tensions, lightning performance (i.e., OPGW wires), insulation performance, reliability requirements and maintenance issues.

2.1.2 Regulatory Codes and Standards

The NESC C2 *National Electrical Safety Code* (3) is the primary regulatory document that addresses most electrical and mechanical aspects dealing with the design, installation, and operation of equipment in high voltage corridors. In particular, the NESC document addresses grounding methods, minimum clearances and approach distances, structural loading, mechanical strength requirements, safety rules for installation, and maintenance. However, a detailed description of the rules and specifications addressed in the NESC C2 standard is not included in this report.

The IEEE Standard 1138-1994 IEEE *Standard Construction of Composite Fiber Optic Ground Wire (OPGW) for Use on Electric Utility Power Lines* (2) addresses the construction of OPGW aerial wires. The IEEE Draft P1222 Standard *All-Dielectric Self-Supporting Fiber Optic Cable (ADSS) for Use on Overhead Utility Lines* (not yet published) includes a variety of tests to evaluate the performance of non-metallic aerial optical cable under laboratory conditions. Standardized tests evaluate the transmission, mechanical, and electrical performance of the cables and include among others, tracking resistance, galloping, and aeolian vibration tests. Most of the tests included in the standard are very much aligned with the standard tests typically performed on OPGW aerial wires, which are significantly different in construction from ADSS and WRAP aerial cables. While the current draft standard addresses minimum performance requirements, it does not address analysis, design, or installation issues of using aerial fiber optical cables and wires in high voltage corridors.

At the international level, the IEC and related bodies provide standards that address optical fibers, aerial cables, connectors, couplers, switches, relays, and others. IEC Technical Committee 86A (TC 86A) covers the development of recommendations for optical fibers and cables while TC 86 B addresses fiber optic interconnecting devices and passive components. At the same time, IEC publication 793 establishes a set of uniform requirements for the geometrical, optical, transmission, mechanical, and environmental properties of optical fibers that are used in telecommunication equipment.

IEC publication 794 covers the manufacturing and performance of fiber optic cables. The first part contains measurement methods to determine mechanical and environmental characteristics. The second part describes single fiber cables for indoor use with applications such as transmission equipment, telephone equipment, data processing equipment, and communication and transmission networks. Finally, the third part of the publication regulates construction issues, acceptable dimensions, and packaging.

The IEC also has standards for related equipment such as attenuators, connectors, switches, and splices. IEC publication 869 describes the optical, mechanical, and environmental test and measurement methods used for the evaluation of optical attenuators. IEC 874 describes requirements for optical detachable connectors. IEC 875 specifies minimum requirements for optical branching devices that typically do not contain opto-electronic or other transducing elements. Last, IEC publication 876 describes minimum performance requirements and optical, mechanical, and environmental test methods for fiber optic switches.

2.1.3 Summary Evaluation

Currently, it appears that there are no comprehensive fiber optic technology application guidelines that can be used by electric utility engineers as reference documents for the integration of aerial fiber optic cables or wires into high voltage corridors. Based on the review, it appears that a significant amount of information and utility experience exists in the literature. Unfortunately, the majority of the information is distributed through a large amount of reference material that makes it extremely difficult and time consuming for most utility engineers to use the information productively in today's competitive business environment.

2.2 Product Description

Optical fibers provide the communications medium of aerial fiber optic cables and wires. By its very nature, optical fibers are extremely fragile when drawn into a hair-like strand. In order to operate as a reliable high quality component, the fiber must be free of impurities and protected from mechanical stresses.

An optical fiber is composed of a light guiding core surrounded by cladding. Both the core and the cladding are typically made of high purity glass typically derived from doped germanium or pure silica. The core and the cladding are then surrounded by one or two protective coatings of Acrylate that improves the strength characteristics of the optical fibers.

Two main types of optical fiber exist: a) single mode; b) multi mode. In a single mode optical fiber, the fiber core is small enough that only one mode of light can travel through the core at any one time. In a multi mode fiber, the fiber core is large enough that multiple modes of light can travel through the core at different paths and lengths. It should be noted that the attenuation of the signal in single mode is significantly lower than in multi mode fibers. Consequently, in power utilities, where fiber optic systems are usually point to point over large distances, single mode fibers are preferred since they require substantially fewer repeater stations which reduces the cost of a communication system significantly. Additionally, single mode fiber also has a higher data transmission capacity than multi mode fiber.

When combined with a method of construction suitable to the high strength, high voltage environment of utility corridors, aerial fiber optic cables and wires provide superior performance and reliability in communication networks because:

- Fiber optic communication cables are neither subject to electromagnetic interference nor do they cause any interference.

- Aerial fiber optic cables and any related equipment can be electrically insulated from system components.

- The technology offers very long information transmission distances of up to 80 km (50 miles) without requiring the use of repeaters.

- Fiber optic technology offers extremely high transmission capacity which can result in data transfer of information at rates of up to 3 gigabytes per second (Gbps).

2.2.1 Manufacturers

There are a number of manufacturers (i.e., an attempt was made to identify suppliers of major presence in the North American marketplace; no attempt has been made to provide a complete list of all suppliers) that currently produce aerial fiber optic ADSS, OPGW, and WRAP cables that can be used in high voltage corridors. These manufacturers, listed in alphabetical order, are:

- Alcoa-Fujikura, Ltd.
- BICC Cables
- Brugg Telecom
- FOCAS, Inc.
- Lucent Fitel/Phillips Fitel Technologies
- SIECOR Corporation
- SIMPLEX Technologies

Alcoa-Fujikura, Ltd. is a total systems provider of passive fiber optic products to the telecommunication, cable TV, electric utility, and data communication industries. The company was founded in 1985 and constitutes a joint venture between Alcoa, Inc., and Fujikura Limited. Alcoa-Fujikura, Ltd provides fiber optic cables, fusion splicers, connectors, accessories, and engineering and support services.

The BICC Cables group is an international business conglomerate providing products and services for infrastructure development in power, communications, building, and transport. In the past, BICC has produced cables for energy, telecommunications, electronic, and high-performance aerospace and defense applications.

The Brugg Telecom group of companies have manufactured cables since 1896, situated in the Swiss town of Brugg just west of Zurich, Switzerland. Brugg Telecom has manufactured fiber optic cables since the early eighties at various locations including Switzerland, United States of America, Australia, and Israel.

FOCAS Inc, originally founded as a division of Raychem Corporation, is currently a division of the Cookson Group, a multi-national materials company headquartered in England and the United States of America. FOCAS offers a wide variety of ADSS, OPGW, and WRAP aerial cables designed for use in high voltage corridors.

Lucent Fitel/Phillips Fitel Technologies, two companies of the Fitel group, headquartered in North America, are manufacturers of fiber optic cable and wire. Lucent Fitel manufactures loose tube technology ADSS cables and related accessories, while Phillips Fitel manufactures OPGW wires and related accessories for long distance carriers, electric utilities, municipal, state, and government entities, and private networks.

SIECOR Corporation, founded in 1977, is a manufacturer of fiber optic cables and accessories for voice, data, and video communication applications. SIECOR is headquartered in Hickory, North Carolina, and owned equally by Corning Inc. and Siemens Corporation. SIECOR Corporation provides a broad offering of aerial fiber optic cables and accessories for installation of communication systems in high voltage corridors.

SIMPLEX Technologies is a wholly owned subsidiary of TYCO International, Limited. and has been involved in technology development and product manufacturing for over 150 years. Today, SIMPLEX Technologies is mainly involved in communication technology including the manufacturing of all types of aerial fiber optic cables.

2.2.2 All-Dielectric Self-Supporting (ADSS) Cables

ADSS cables must be designed with sufficient tensile strength to maintain minimum clearances and protect the optical fibers from external stresses and strains throughout the predicted service life (7, 8, 101). Consideration must be given to long term fatigue and creep. The support element of ADSS aerial cables is typically glass, Aramide fiber, or both (see Figure 2-1 through 2-3). Metallic strength elements may also be used in other self-supporting aerial cables but are typically not recommended where a parallelism exists between the routes of communication and the power supply cables due to the induction potential on the aerial cable from the phase conductors.

Due to the light weight and high-strength-to-weight ratio, ADSS aerial cables can be utilized on very long spans (i.e., up to 1000 m or 3284 feet) for most climatic loading conditions. The number of optical fibers in ADSS cables is typically higher than the number of optical fibers in OPGW or WRAP aerial cables. Fiber counts usually vary between 24 to 48 fibers for most long distance applications, while local area loops may have fiber counts of up to 288 for ADSS and 144 for OPGW aerial cable. Optical fibers may be bundled, formed into ribbons or individually housed in loose buffer tubes or slots to provide adequate mechanical protection. Typically, the tubes or slots are filled with grease to protect the optical fibers from water penetration.

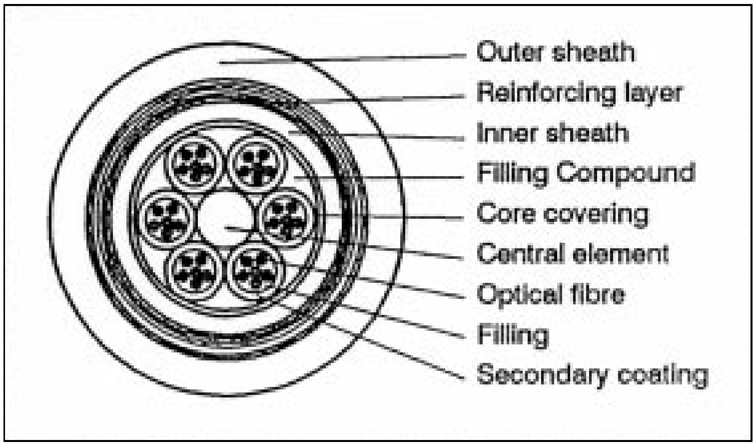

Figure 2-1
Loose Tube Buffered Fiber FRP Reinforced ADSS Cable (Reference 4)

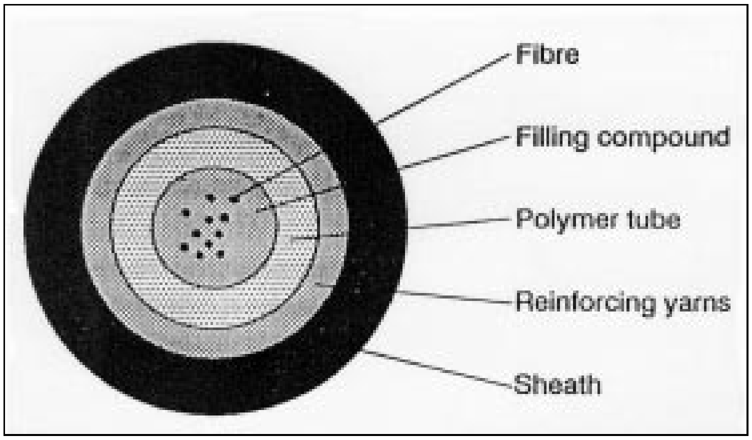

Figure 2-2
Central Maxi Tube Loose Fiber Aramide Reinforced ADSS Cable (Reference 4)

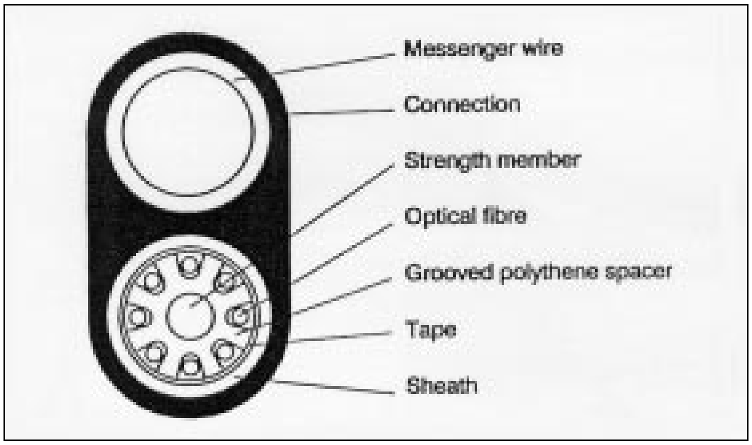

Figure 2-3
Loose/Buffered Tube Messenger Reinforced ADSS Cable (Reference 4)

There are a number of different construction methods used to produce ADSS aerial cables. Figure 2-1 shows an ADSS cable consisting of loose tube buffered fibers stranded around a glass fiber reinforced plastic core surrounded by the inner sheath. Stranded glass or Aramide fibers are applied beneath the outer sheath. Figure 2-2 shows an ADSS cable consisting of a central maxi tube accommodating up to about 24 loosely housed optical fibers. Typically, fibers are inserted into the maxi tube in the manufacturing process with an overlength to avoid excessive fiber stresses.

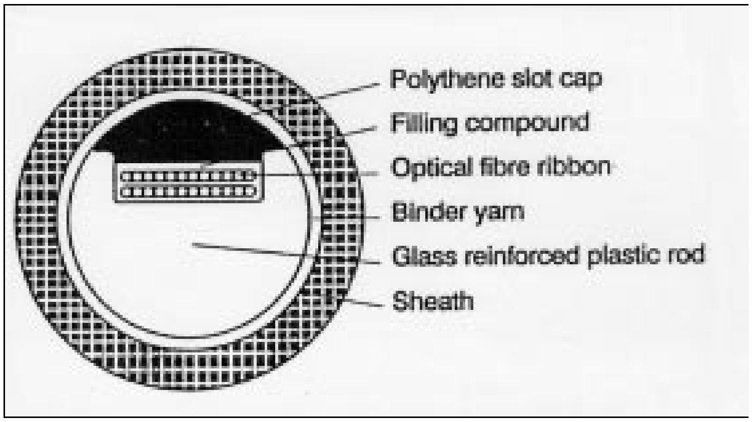

Figure 2-4
Grooved/Hollow Glass Reinforced ADSS Cable (Reference 4)

Figure 2-3 shows an ADSS cable with a loose or tightly buffered optical bundle supporting by a stranded glass or Aramide messenger wire. Typically, the optical unit is connected to the messenger wire at intervals with molded sheath stays.

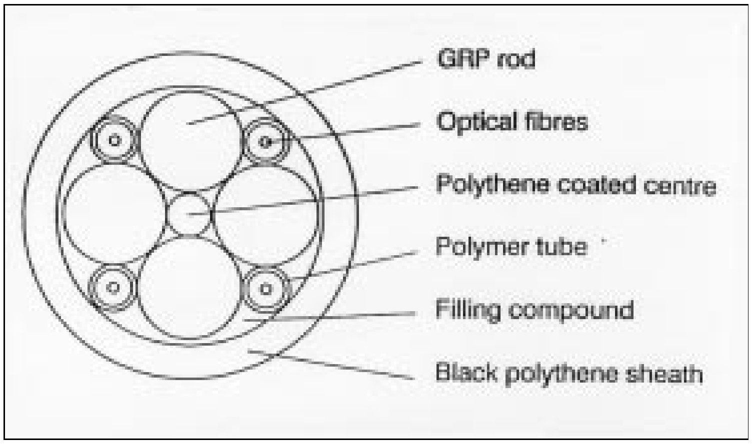

Figure 2-5
Loose/Buffered Tube Glass Reinforced ADSS Cable (Reference 4)

Figure 2-4 shows an ADSS aerial cable made of a grooved or hollow glass fiber reinforcing rod surrounded by an outer sheath. The optical fibers are typically embedded in an optical fiber ribbon that rests in the groove of the reinforcing rod.

Figure 2-5 shows an ADSS aerial cable that consists of multiple glass or Aramide strength members and loose tube buffered fiber cables stranded together inside the outer sheath. Typically, this design process shows to be very flexible which makes it most suitable for applications that require a small turning radius.

2.2.3 Optical Ground Wire (OPGW)

In composite conductors a fiber cable unit containing the optical fibers is either integrated or embedded into a conductor or ground wire. In voltages below 138-kV the composite conductor can also be a phase wire (i.e., as previously mentioned, the discussion of Optical Phase Conductor (OPPC) is not included in this report). However, usually the fiber unit containing the optical fibers is placed inside the ground wire. This type of construction is called an 'Optical Ground Wire' (i.e., OPGW).

OPGW can be a light weight ground wire designed to be used as a static wire replacement or it can be installed in addition to conventional ground wire. The mechanical and electrical requirements for OPGW aerial wires are very similar to requirements for comparable conventional ground wires. Currently, the number of optical fibers that can be readily fitted into an OPGW aerial wire construction can reach up to 144 fibers.

OPGW aerial wires can be differentiated in various ways. The most common way to differentiate between the different types includes: a) loose versus tight buffering; b) solid core versus tubular core; c) fibers inside metallic tube versus fibers inside plastic tube (i.e., closed versus open construction). Metallic tubes are either welded or extruded while plastic tubes are always extruded. In some OPGW constructions several tubes are stranded over a strength element while other constructions favor a single tubular core. Fibers inside the tube are either loosely or tightly buffered. Typically, in OPGW aerial cables that are subjected to environmental as well as fault current induced stresses the packing of the optical fiber is an essential factor. The advantage of tight buffering is the construction of a small overall conductor diameter, while the advantage of loose buffering is that the optical fibers are not subjected to tensile stresses typically caused by conductor elongation.

Metallic tubes provide a hermetic protection against water and hydrogen penetration. However, if there is any hydrogen generation on the inside of the tube the moisture is also unable to evaporate. In plastic tube constructions, the possible effects of water and hydrogen have to be mitigated through the selection of the materials such as tape and filler compounds. Typically, the tubes are filled with compound material for water and vibration protection. However, in some constructions the optical fibers or tubes are isolated from direct contact with metallic current carrying parts. Often, plastic tubes are faster and easier from an installation point of view and the unit can be used as a cable itself inside buildings.

The metallic wires have to give the OPGW aerial cable enough conductivity to carry fault currents, and the strength to withstand mechanical stresses. Therefore, aluminum, aluminum alloy, galvanized steel, aluminum clad steel wires or a combination of any of them are typically used. Two armoring layers can be used to prevent the effects of residual torsion from the laying of the strands, while if a single layer is used it is recommended to use an anti-rotation device during installation. At the same time, the use of two layers of stranding results in a smaller temperature change in the ground wire as a result of a fault current or lightning strike.

The OPGW aerial wire shown in Figure 2-6 takes advantage of plastic tube construction in which the optical fibers are placed loosely with overlength. This particular cable design is relatively sensitive to temperature changes and has a relatively low crush resistance. However, in most cases it is possible to reverse any deformations incurred on the aerial wire. The maximum number of optical fibers for this construction is typically limited to 12 fibers.

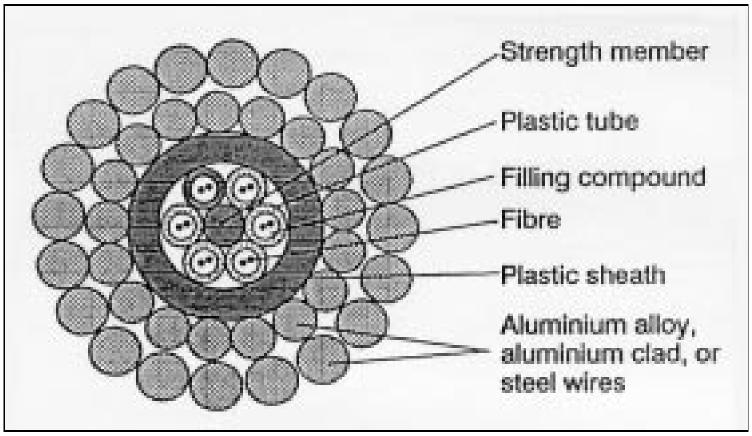

Figure 2-6
Stranded Plastic Tubes - Plastic Sheath OPGW (Reference 4)

The OPGW in Figure 2-7 demonstrates a typical maxi tube design in which the fibers are housed loosely with overlength. This design typically requires a very sticky compound to avoid fiber and compound movement that can make the compound unworkable in low temperature conditions. Crush resistance is usually relatively low but deformations are reversible once they occur. Fiber counts of up to 48 fibers are possible and splicing is usually achieved quickly.

Figure 2-8 shows a later evolution of an OPGW construction incorporating a straight plastic tube. The hollow channel is shaped in a spiral inside the tube to emulate stranding. Optical fibers are usually loosely housed and the oval channel is filled with

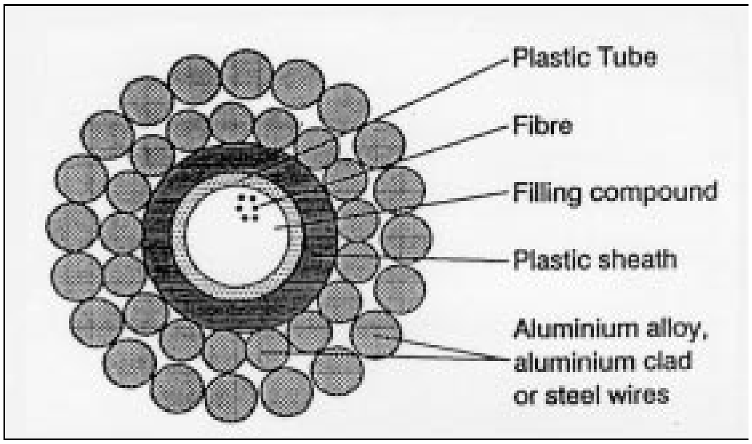

Figure 2-7
Straight Plastic Maxi Tube - Plastic Sheath OPGW (Reference 4)

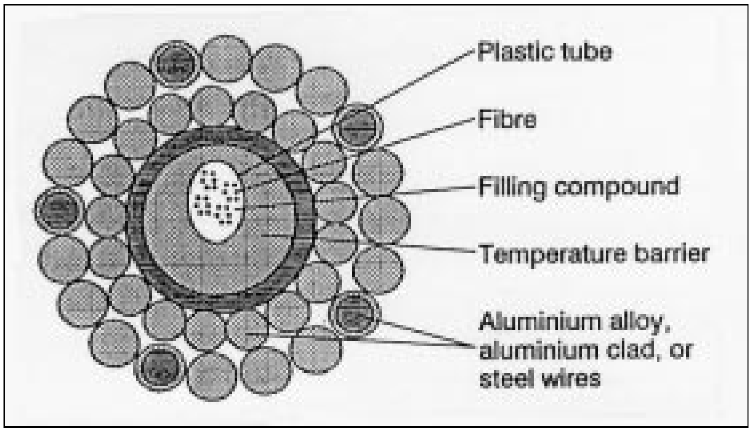

Figure 2-8
Straight Plastic Tube - Spiraling Hollow Channel OPGW (Reference 4)

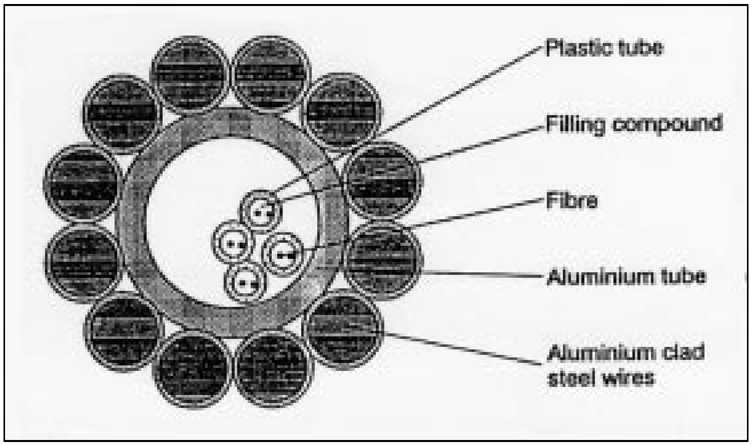

Figure 2-9
Stranded Plastic Tubes - Aluminum Tube OPGW (Reference 4)

a compound. As a result of the small channel, a filling compound can be used that exhibits a good temperature range eliminating the problems associated with the design shown in Figure 2-7 (i.e., sticky compound). Controlled optical fiber overlength (i.e., the length of fibers in excess of the strength member length) of up to 48 fibers is obtained by the biasing of the fiber and the stranding. The crush resistance of this particular design is usually high and deformations are reversible in most cases.

The OPGW design shown in Figure 2-9 is characteristic of the original OPGW design that combines the use of stranded plastic tubes and a central aluminum tube. The stranded plastic tubes containing the optical fibers are loosely housed inside an aluminum tube but can also be stranded around a central element. Tubes are usually filled with a compound and fiber overlength is controlled through biasing and stranding. Typically, crush resistance is relatively high but deformations are irreversible and collapse of the tube is possible if minimum bending radius of wire is not carefully maintained. Fiber counts of up to 36 fibers are typical but the splicing process is relatively slow.

The OPGW aerial wire design shown in Figure 2-10 utilizes a central helically grooved core of aluminum surrounding compound filled plastic buffer tubes that contain the primary coated optical fibers. Typically, the optical fibers are not strained since they move radialy whenever the conductor changes length. This type of design has a very high crush resistance and is relatively easy to splice. This design allows for very high fiber counts with diameters comparable to traditional ground wires.

The OPGW in Figure 2-11 has a grooved or slotted aluminum spacer in which optical fibers are packed inside compound filled grooves. Typically, the fibers are packed relatively tight (i.e., little or no overlength). However, with low fiber counts it is also possible to pack the fibers loosely. Crush resistance is usually very high but deformations can not be reversed once they occur. Fiber counts of up to 48 fibers are possible, but the aluminum tube and spacer can get very hot during a fault which may require special fiber coatings.

The OPGW aerial wire in Figure 2-12 utilizes loosely packed optical fibers inside thin, small diameter compound filled steel tube(s). Typically, the steel tubes are welded and the optical fibers are inserted with overlength. The crush resistance of these OPGW wires is relatively good, but any deformations are irreversible. Splicing of the cable is efficient and the use of the aluminum strands prevents significant temperature changes as a result of a fault.

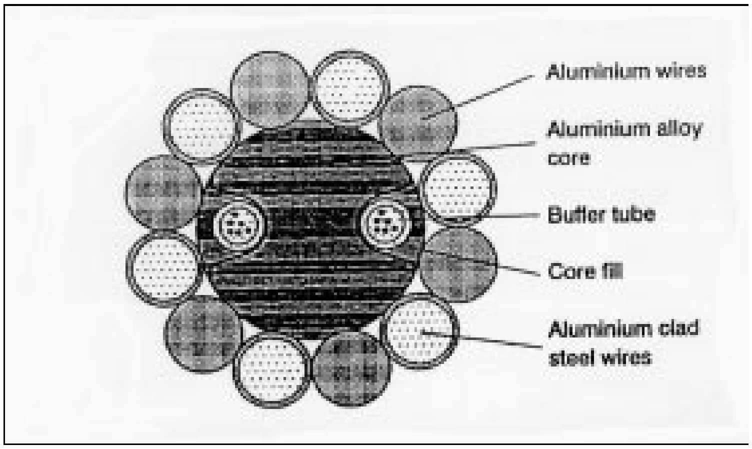

Figure 2-10
Slotted Aluminum Spacer - Non Metallic Buffer Tubes OPGW (Reference 4)

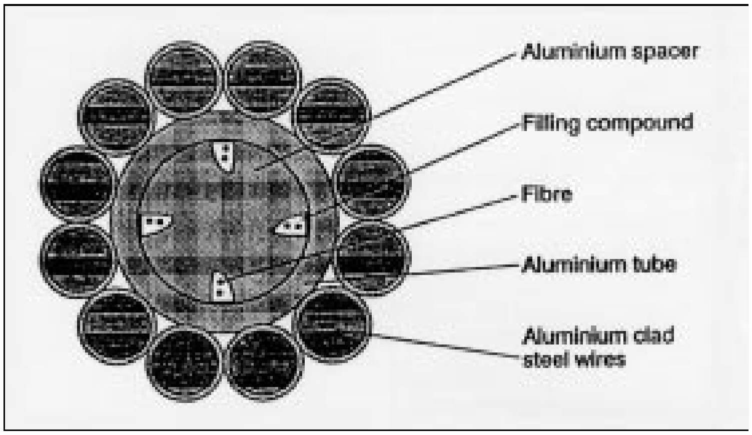

Figure 2-11
Grooved Aluminum Spacer - Aluminum Tube OPGW (Reference 4)

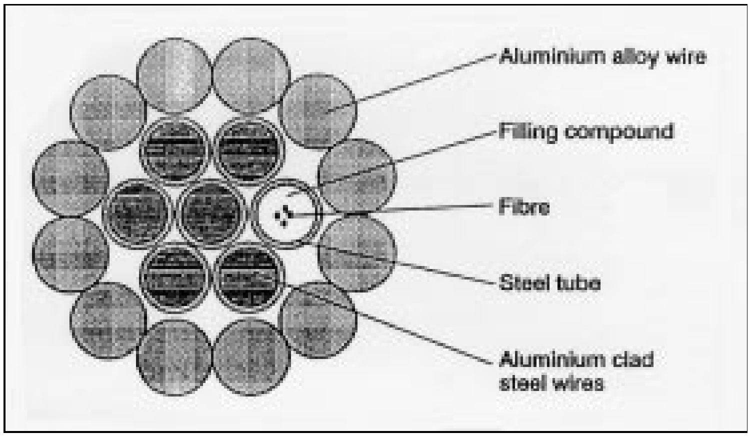

Figure 2-12
Thin Steel Tube OPGW (Reference 4)

2.2.4 Wrap-Type Fiber Optic Cables (WRAP)

WRAP aerial fiber optic cables can be fastened to or wrapped around the existing phase or ground wire as shown in Figure 2-13. Typically, the wrapping-type system is the only system still used in today's installation of communication networks. These fiber optic cables are usually lightweight since they rely on the strength of the conductor or ground wire for support. The number of fibers typically used in WRAP aerial cables ranges from 6 to 24 fibers.

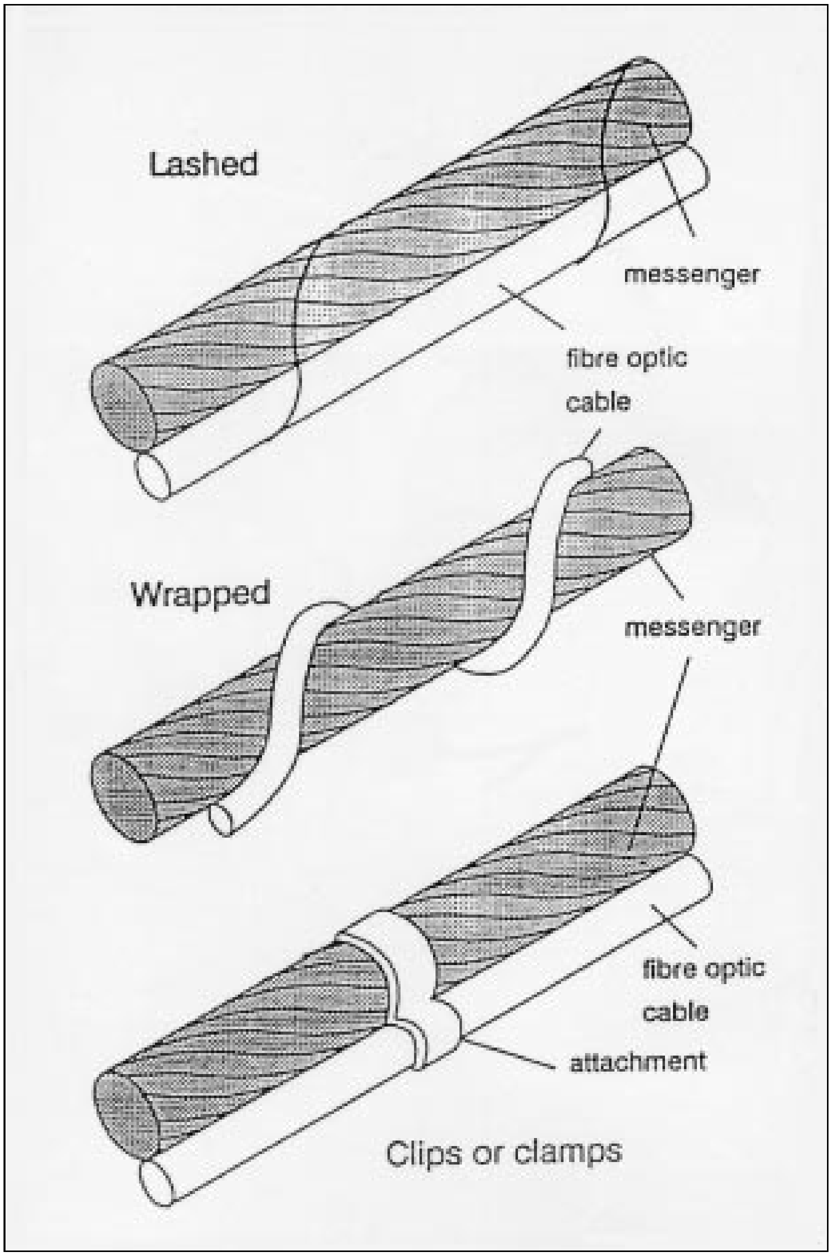

Figure 2-13
WRAP Aerial Fiber Optic Cables (Reference 105)

Wind tunnel tests (1, 7, 44, 51, 68) have shown that there are no aerodynamic instabilities such as un-iced galloping associated with the addition of WRAP aerial cables on conductors and ground wires. To the contrary, it was determined that the helical wrapping tends to reduce the level of aeolian vibration and the incidence of iced galloping if compared to the performance of standard ground wires. Generally, an attempt is made to limit the diameter of the WRAP aerial cable to 1/3 of the diameter of the support wire. Experience has shown (45, 103) that this will not result in any appreciable differences (i.e, less than 20 %) in the magnitude of the ice and wind loads calculated for most spans.

2.2.5 Electrical Performance Specifications

A limited number of electrical performance tests are usually carried out to confirm the mechanical characteristics of ADSS, OPGW, and WRAP aerial cables and wires when subjected to stresses created by the electrical environment in high voltage corridors. These tests are:

- Fault Current/Lightning Test (These tests are typically performed in accordance with utility or applicable standard test procedures. The purpose of the test is to evaluate the effects of fault currents and lightning strikes on the performance of aerial cables and wires.)

- Salt Fog/Erosion Test (The objective of the test is to determine the resistance of ADSS and WRAP aerial cables and associated hardware to the effects of erosion and tracking. Typically, components are subjected to the maximum mechanical and electrical stresses expected to be encountered during the life cycle of the component. The test is particularly important where ADSS or WRAP aerial cables are to be installed on power lines with voltages greater than 138-kV.)

2.2.6 Mechanical Performance Specifications

Fibers used in the manufacturing of optical cables and wires for electric utility networks are normally standard telecommunication single mode fibers. However, multi mode or dispersion shifted single mode fibers are frequently considered for specific applications. Typically, the fiber manufacturer, which may be different from the cable or wire manufacturer, ensures that the fibers meet nationally and internationally accepted standards and performance requirements. Certificates of conformity and attenuation details are usually provided with each product in addition to random test results at specified signal wavelengths.

To adequately address opto-mechanical and mechanical performance of aerial fiber optic cables it is necessary to address the characteristics of the optical fibers as well as the performance of the assembled cable or wire. These characteristics are defined by tests such as:

- Attenuation IEC 793-1 (Addresses the loss per km in dBs for carrying wavelengths, temperatures, etc.. Particularly, the attenuation performance of the first and second window is critical to the overall performance.)

- Temperature Cycling Test IEC 793-1-D1 (Identifies the performance of optical fiber at varying temperatures.)

- Microbending Sensitivity IEC 793-1-C3 (The sensitivity of the optical fiber to microbending is critical due to increased attenuation as a result of an increased sensitivity.)

- Frequency Response IEC 793-1-C2B (The frequency response of multi-mode fiber is normally specified to adhere to minimum requirements in order to establish a usable bandwidth.)

- Other Parameters (Further specifications are usually defined that address the Cut-off Wave Length IEC 793-1-C7, Mode Field Diameter IEC 793-1-C9, Fiber Dispersion IEC 793-1-C5, Numerical Aperture IEC 793-1-C6, and Macrobending Sensitivity IEC 793-1-C11.)

Typically, the optical fiber proof test which establishes the durability of the fiber is used as an accepted reference by manufacturers. This test is usually carried out strictly in accordance with IEC 793-1-B1. Specifications for other parameters usually considered include:

• Bending	IEC 793-1-B3
• Abrasion	IEC 793-1-B4
• Visual Examination	IEC 793-1-B5
• Core Concentricity	IEC 793-1-A3
• Stripability	IEC 793-1-B6

Generally, ADSS, OPGW, and WRAP aerial fiber optic cables and wires to be used in the electric utility industry are tested at least three different times during the manufacturing process. First, each cable and wire design should be thoroughly tested prior to full-scale production to verify the design of the component. Second, production run samples should be continuously sampled at random and tested to evaluate the performance of the manufactured product. Last, tests should be performed on site just prior and after the installation to evaluate the performance of the components as well as of the communication system.

The qualification tests typically carried out are dependent on the environmental conditions that are expected to be encountered during the service life of the product. Additionally, the anticipated method of installation will also define the magnitude of the mechanical stresses acting on the cable that have to be verified during the qualification test period. Most of the qualification tests that are usually required in the characterization of a cable or wire are described in detail in IEC 794 or in the applicable IEEE standard for OPGW aerial cables. The IEC 794 qualification tests are:

- Aeolian Vibration Test (The objective of the aeolian vibration test is to assess the fatigue performance of the cable and the optical characteristics of the optical fibers when subjected to aeolian vibrations.)

- Cold Temperature Flexure Test (As well as cyclic bending and flexibility tests carried out in accordance with IEC 794-1-E6, are usually conducted to ascertain the flexing of cables or wires at low temperatures, typically at a temperature equal to the minimum expected working temperature of the fiber element.)

- Corrosion Salt Fog Test (The objective of the corrosion test is to assess the mechanical degradation of the metal components in an accelerated life simulation using a salt fog environment.)

- Creep Test (The objective of the creep test is to evaluate the long term sag-tension behavior of the aerial cable under controlled conditions. The creep test should be performed for a minimum of 1000 hours at 50 % of the maximum working load. Usually, elongation and time are monitored and recorded.)

- Crush Resistance (The objective of this test is to evaluate the crush resistance of an ADSS, OPGW, or WRAP aerial cable. Usually, tests are carried out in accordance with IEC 794-1-E3.)

- Cut-Through Test (This is a specific test for polymer coated cables. The objective of this test is to examine and evaluate the ability to withstand damage caused by pressure from sharp abrasive edges.)

- Flexibility/Cyclic Bend Testing (The purpose of these tests is to evaluate the minimum bending radius and other general handling characteristics of the cable or wire. These tests are normally carried out in accordance with procedures set out in IEC 794-1-E6 and IEC 794-1-E11 in atmospheric conditions.)

- Galloping Test (Constitutes a test to identify galloping characteristics of aerial cables and wires.)

- Impact Test (Test make-up varies for different cable and wire types. The standard impact test should be performed in accordance with IEC 794-1-E4.)

- Stress-Strain Test (Sag-tension relationships are critical parameters in the analysis, design, and installation of aerial fiber optic cables and wires. Typically, the cable or wire is cyclically loaded at various levels of stress while the cable or wire strain, attenuation, and optical fiber strain are monitored and recorded.)

- Temperature Cycling Test (This test is used to assess the suitability of cables or wires to operate at various temperatures. Usually, attenuation measurements are taken at various stages during the test procedure. The test should be performed in accordance with IEC 794-1-F1.)

- Torsion Test (The objective of the test is to assess the cable or wire's torsional characteristics including the susceptibility to twist under tensile loading. The test should be performed in accordance with IEC 794-1-E7.)

- Water Blocking Test (This test is designed to examine the effects of water penetration in the presence of sheath damage on the aerial cable or wire. The test should be performed in accordance with IEC 794-1-F5.)

Routine testing is usually carried out by the manufacturer at various stages throughout the production of the optical cable. The information obtained from routine testing can be used by the manufacturer and the customer to inspect the ongoing quality and reliability of the product to be used in the high voltage corridor. Also, these tests prevent the manufacturing of fiber optic cable with marginal properties.

Normally, the customer accepts the cables or wires in the field with an attached factory test report. However, most customers require additional attenuation checks on the fibers that are normally carried out with an Optical Time Domain Reflectometer (OTDR) to verify the performance of the optical cable just prior to installation. Once the installation has been completed, another attenuation check is performed on each fiber to verify the functionality of the installed system.

2.2.7 Summary Evaluation

Table 2-1 shows a breakdown of typical material and installation cost of fiber optic aerial cable and wire. Costs are shown for typical aerial cable and wire with either 24 or 48 optical fibers. The majority of the cost is attributed to the cost of the cable itself and the labor involved in the installation. It should be noted that the cost of the aerial cable with 48 optical fibers is not twice as expensive than the comparable item with 24 optical fibers. Generally, the marginal cost of additional optical fibers decreases as the number of fibers increase.

Table 2-1
Typical System Cost

Fiber Count (24 Fibers)	Type of Cable/Wire					
	ADSS		OPGW		WRAP	
	($/m)	($/ft)	($/m)	($/ft)	($/m)	($/ft)
Planning/System Design Cost	0.50	0.15	0.50	0.15	0.50	0.15
Cable/Wire Cost	7.00	2.13	9.00	2.74	6.00	1.83
Installation Material Cost	1.00	0.30	1.00	0.30	1.00	0.30
		0.00		0.00		0.00
Labor Cost (Installation)	4.00	1.22	3.50	1.07	2.50	0.76
Labor Cost (Splicing of Fibers)	0.75	0.23	0.75	0.23	0.75	0.23
Labor Cost (System Commissioning)	0.25	0.08	0.25	0.08	0.25	0.08
Total Cost	13.50	4.11	15.00	4.57	11.00	3.35

Fiber Count (48 Fibers)	Type of Cable/Wire					
	ADSS		OPGW		WRAP	
	($/m)	($/ft)	($/m)	($/ft)	($/m)	($/ft)
Planning/System Design Cost	0.50	0.15	0.50	0.15	0.50	0.15
Cable/Wire Cost	10.00	3.05	12.00	3.65	9.00	2.74
Installation Material Cost	1.00	0.30	1.00	0.30	1.00	0.30
		0.00		0.00		0.00
Labor Cost (Installation)	4.00	1.22	3.50	1.07	2.50	0.76
Labor Cost (Splicing of Fibers)	1.50	0.46	1.50	0.46	1.50	0.46
Labor Cost (System Commissioning)	0.40	0.12	0.40	0.12	0.40	0.12
Total Cost	17.40	5.30	18.90	5.76	14.90	4.54

A summary of pertinent product information on ADSS, OPGW, and WRAP aerial cables in high voltage corridors is provided in Table 2-2. The importance of each piece of information is also provided.

Table 2-2
Product Description Summary Evaluation

Consideration	OPGW		WRAP (on ground wire)		ADSS	
	Relative Importance	Comments	Relative Importance	Comments	Relative Importance	Comments
Manufacturers	Low	A large variety of products are offered by various manufacturers.	Low	A large variety of products are offered by various manufacturers.	Low	A large variety of products are offered by various manufacturers.
Cable and Wire Construction	Low	A large variety of different cable and wire designs are offered by various manufacturers.	Low	A large variety of different cable and wire designs are offered by various manufacturers.	Low	A large variety of different cable and wire designs are offered by various manufacturers.
Electrical Performance Specifications	Low	IEEE Std 1138-1994 covers the electrical performance specifications of OPGW wires.	Low	Currently, there is no IEEE standard for WRAP wires.	Medium	Currently, there is no IEEE standard for ADSS cables (draft standard is forthcoming). Minimum track resistance not clearly established.
Mechanical Performance Specifications	Low	IEEE Std 1138-1994 covers the mechanical performance specifications of OPGW wires.	Low	Currently, there is no IEEE standard for WRAP wires.	Medium	Currently, there is no IEEE standard for ADSS cables (draft standard is forthcoming). Fatigue endurance limits not yet defined.

2.3 Electrical Considerations

2.3.1 Placement

The location of an ADSS cable must be selected to permit adequate clearances from the phase and ground conductors and to minimize the electric field on the sheath (1, 32, 79, 103). Additionally, placement of ADSS aerial cables is determined by other factors that include clearances to ground, the electric field strength or the space potential to which the cable will be exposed, and the strength of the structural attachment point.

The strength of the electric field or the value of the space potential at the location of the ADSS cable is a deciding factor in applications at voltages greater than 230-kV (8, 14, 85). Although, ADSS cables have been installed successfully in many cases at voltages up to 150-kV, several early designs installed at higher voltages (i.e., 230-kV and above) suffered significant damage close to the grounded supports. It has been argued (7, 8, 15, 23, 29, 33) that capacitively induced voltages drive currents along the cable sheath causing dry band arcing and eventual thermally induced damage to the cable sheath. Other damage mechanisms include degradation of the ADSS cable by corona activities at the tips of armor rods and other hardware, and corona on water droplets under wet conditions.

Placement of OPGW aerial cables is typically determined by their alternate function as ground or shield wire. The OPGW is placed in the normal location of the ground wires, since it is intended to serve two different functions. WRAP aerial cables are also normally wrapped around the regular ground wire. Hence, WRAP aerial cables are subjected to the same environment as OPGW aerial cables. The two functions served by OPGW and WRAP cables are:

- Regular Ground Wire
- Fiber Optic Communication Cable

2.3.2 Electrical Modeling and Analysis

Electric field modeling and analysis of OPGW and the WRAP fiber optic cables is not typically required beyond traditional analysis normally performed for regular ground wires. However, in unusual situations in which ground wire corona occurs, WRAP aerial cable placement can be analyzed using a 2-D electrostatic analysis.

Detailed 3-D modeling and analysis of electric field patterns near the structures are recommended in order to identify locations that will minimize the electric field induced degradation of ADSS aerial cable. Otherwise, catastrophic failures within a short period of time (2 to 10 months) can result. However, 3-D analyses require significant resources which may not always be available prior to placement of aerial optical cables and wires. At a minimum, a 2-D space potential calculation should be used to identify the most suitable placement location for standard and angle suspension structures. At the same time, it should be realized that a more rigorous 3-D analysis may allow the placement of ADSS cables in potentials up to 40 kV (i.e., calculated in a 2-D analysis) by considering the shielding effect of the transmission structure.

The problems observed in the field resulted in limited research work both in Europe and the United States. Using a 3-D field calculation program, Bonneville Power Administration (BPA) determined the electrical field distribution around the towers and at the ends of the armor rod assemblies. The model included the tower, conductors and fiber optic cable armor rods. The field calculation verified that corona is likely to occur at the tips of the armor rods whenever the ends of the armor rods do not all terminate at the same location along the length of the cable. BPA and other utilities have observed corona caused deterioration on fiber optic cables installed on 345-kV or 500-kV transmission lines. In one instance, corona discharges severed the cable after only a few months of operation.

BPA sponsored a project at Arizona State University (ASU) in 1995-1996 to perform experimental studies and identify the severity of the corona caused fiber optic cable deterioration. The field conditions of a high voltage line were replicated in the high voltage laboratory and nine cable assemblies were tested for more than 4000 hours.

The results of the experiment showed that corona discharge can produce a dangerous deterioration of fiber optic cables. The appearance of deterioration in the laboratory is similar to the deterioration observed in the field. The amount of deterioration depends on the field strength and the duration of exposure. The amount of deterioration roughly correlates with the intensity of the partial discharges, measured in Coulombs. The test results suggest that the corona punctures the cable jacket after seven to ten years, assuming linear degradation.

The discussions during a recent EPRI workshop (December 12, 1996, Arizona State University) indicated that the failure of ADSS fiber optic cables in high electric field environments is an industry-wide problem. Houston Light and Power, Consolidated Edison in New York and other utilities in England and Germany observed problems similar to those of BPA. The analysis of failures and of the results of the BPA/ASU and manufacturer performed tests revealed that long term exposure to high electric fields initially causes cable jacket surface discoloration, followed by surface erosion, then the puncture of the jacket, and ultimately the severing of the cable. Two physical phenomena are thought to cause the cable failures:

- Corona discharge at the tips of assembly rods that are not all terminated at the same location on the cable (i.e., one rod sticks out further than others); and,

- Dry band arcing on the surface of the cable under polluted conditions

BPA concentrated their observations and experiences on the corona phenomena. Europeans believe that dry band arcing is the primary cause of the cable failures (11, 12, 13, 14). Analysis of the two phenomena suggests that the prevailing climatic conditions are likely to have a major effect on the fiber optic cable failures.

Modeling of the electric field needs to be three-dimensional near the structures, since the electric field does not possess sufficient symmetry (such as rotational symmetry) to allow accurate, simplified two-dimensional calculations. The region of interest is the space at the tip of metallic hardware that is close to the ADSS cable, since this is where the strongest fields are expected. The metallic hardware may be the armor rods, clamps or other attachment hardware. The hardware itself may be at ground potential, but the electric field (i.e., the gradient of the potential) at the tips and corners of the armor rods may still be quite high. In addition, metallic dampers installed on the ADSS cable may have no connection to ground, in which case the induced voltage on them may result in a high electric field at the tips and between the electrically floating parts and the grounded parts.

The above discussion indicates that the region of interest need not be large in physical dimensions, but its complicated geometrical details need to be represented precisely for accurate field calculations. Hence, the computational effort can be quite significant. No closed-form analytical solutions are available. The region of interest may be unbounded on several sides, and may have well-defined physical and electrical boundary conditions in other locations. Computational methods most suitable to tackle this problem include the Finite Element Method (with ballooning or other means of treating unbounded regions), the Boundary Element Method, and the Charge Simulation Method. The most suitable software candidates for this application include the commercially available ANSOFT programs and specialized software developed in-house by some utilities (such as the BPA program).

2.3.3 Corona

The outer plastic sheath of an ADSS aerial cable is subject to erosion by discharges when placed in the electric field of the phase conductors of the overhead power line (12, 17, 18). While the influence is negligible at lower voltage levels, problems have been observed on lines with higher voltage ratings. Typically, the surface of the ADSS cable sheath changes in appearance and structure near the dead end and armor grip suspension points. These changes indicated a degradation of the ADSS sheath surface. Typically, the damage of the sheath, normally black with high density polyethylene, arises within a few weeks to months. Consequently, the sheath material of ADSS aerial cables must be resistant to electrical discharges.

Laboratory tests (9) showed significant changes in the mechanical properties of some ADSS jacket materials after 2000 hours of exposure. It appears that jacket materials with efficient combinations of Alumina Tryhydride, UV stabilizer, and cross-link density have a sufficient resistance to tracking in space potentials of up to 25 kV.

Several methods of preventing or diminishing corona activities on ADSS aerial cables exist (19, 27). One method consists of placing metallic electrodes on the ADSS cable in the high electric stress regions. The electrodes provide a path for discharges away from the cable surface, which protects the cable. However, the applicability of this mitigation method for ADSS aerial cables has not yet been put to practice and should be evaluated in a realistic environment for an extended time period. A second method consists of the placement of large doughnut-shaped devices, usually cylindrical in shape, on the cable to provide shielding from the high electric fields and to prevent discharges that can damage the cable.

Apart from the traditional issues related to corona on normal ground wires, there are no additional considerations related to corona for OPGW. The optical fibers in the OPGW are shielded from electric field and corona activities, and the fibers are inherently immune to electric disturbances from corona activities on the OPGW. Similarly, the WRAP cable also does not present any corona related problems beyond the traditional considerations of minimizing corona on ground wires and attachment hardware.

2.3.4 Insulation

The sheaths of ADSS cables installed freely suspended on power lines are subjected to electrical activity. The surface leakage currents are modest, but they may be driven by substantial capacitively coupled voltages. In misty conditions, or during drying after rainfall, large potential differences can appear across small lengths of dry cable, causing local arcing. ADSS aerial cables adjacent to grounded fittings are particularly vulnerable. Of course, surface leakage currents and the voltages available for dry band arcing are a function of the system voltage, the line geometry, and the location of the ADSS cable.

The ADSS cable is normally installed ten to twenty feet below the phase wires. It parallels the phase wires and is subject to induced voltages. For this reason, the construction of the ADSS should not include metallic components such as steel strands for mechanical strength. At the structures, the ADSS is supporting by armor rods. The armor rods surround the cable, distributing the mechanical loads more evenly. Although the armor rod assemblies are grounded, they are subjected to a high electric field (8, 14). Particularly high field concentrations have been observed at the tips of the individual rods of the assembly. This high field may initiate corona discharge, which can endanger the fiber optic cable. In the field utilities observed corona caused deterioration on fiber optic cables installed on 345-kV or 500-kV transmission lines.

Additional insulation on the ADSS does not solve this problem. In order to avoid degradation due to corona, the ADSS should be placed in locations with low electric field as previously discussed in Sections 2.3.1 and 2.3.2.

Since the ADSS is normally installed below the phase wires, it is not typically subject to lightning strikes. Also, since the ADSS normally does not contain metallic parts, there are no issues related to ground loops or GPR. However, the insulation of the ADSS may become sufficiently contaminated to conduct axial current that may pose a hazard to personnel. Outer insulation of the ADSS should be selected to avoid this problem if possible, and maintenance personnel should be trained to recognize the possible hazards and to treat the contaminated ADSS as a conducting cable if necessary or as required by local safety regulations.

The OPGW can be electrically bonded to the grounded structure or it's grounding system, or it can be electrically insulated from ground. Insulated ground wires were used traditionally as part of Power Line Carrier (PLC) communications systems, or as a means of reducing system losses by eliminating induced ground wire currents. The PLC communications option becomes obsolete since the OPGW can be used for utility communications, but some old systems may still use PLC systems to avoid retrofit costs. In either case, however, the OPGW does not present new or unusual insulation problems as far as the OPGW itself is concerned.

The fiber optic cable is not specifically insulated from the metal strands of the OPGW. The optical performance of the fiber optic cable is not affected by small radial or axial potential differences on the cable. Protection against lightning strikes is provided by the outer layer strands of the OPGW or the outer layer of the fiber optic cable, which should be at least 2 mm (5/64 inch) thick. Issues of insulation from local grounds to avoid ground loops in the communications electronics, and from Ground Potential Rise (GPR) effects are covered in separate sections of this report.

Similar to OPGW, the WRAP fiber optic cable can be electrically bonded to the grounded structure or it's grounding system, or it can be electrically insulated from ground. The WRAP cable can be insulated from structures and grounding systems in order to serve as part of PLC communications systems, or as a means of reducing system losses by eliminating induced ground wire currents. The PLC communications option becomes obsolete since the wrap-type itself can be used for utility communications, but some old systems may still use PLC systems to avoid retrofit costs. In either case, however, the WRAP aerial cable does not present new or unusual insulation problems as far as the cable itself is concerned.

2.3.5 Lightning Performance

Since ADSS aerial cables are normally placed below the phase wires, they are usually not exposed to direct lightning strikes. Also, ADSS cables are free of metal components, resulting in a fault current of negligible magnitude.

OPGW aerial cables are placed at the top of structures and thus experience lightning strikes and short-circuit currents. Typically, it is assumed that the energy in these transients is dissipated safely due to the mass of the aluminum around the optical wire and that the associated heating effect is negligible. However, under the passage of short circuit currents, core temperatures can reach 100°C (212°F), which can cause annealing of the aluminum components resulting in excessive strains (2, 34, 52). It is important that there is no significant change in optical attenuation under these conditions.

Since the majority of these energy transients are caused by fault currents, it is necessary to take the maximum available fault current and the duration of the fault into account in the selection of the OPGW aerial wire. OPGW aerial wires are typically rated using the maximum I^2t value.

Protection of the fibers against lightning strikes is provided by the outer layer of the OPGW or the metal layer of the fiber optic cable, which should be at least 2 mm (5/64 inch) thick. The fiber itself can tolerate very high temperatures, but thermal performance of plastic tubes, fiber coatings and aluminum or aluminum coated steel wires needs to be carefully considered.

The lightning characteristics of WRAP aerial cables are very similar to the characteristics of OPGW wires. However, since WRAP aerial cables are placed on the outside of the ground wire, they are directly exposed to lightning strikes and the metal tube of the cable must be designed to withstand all thermal stresses resulting from such strikes. At the same time, the tube needs to be designed to carry the full magnitude and duration of the fault current since it only parallels the ground wire, which is designed to provide the primary path for the fault current.

2.3.6 Grounding

Since the ADSS used in high voltage environments does not contain metallic parts, there is no question of grounding the cable. However, it must be recognized that the ADSS aerial cable is mechanically attached to grounded parts at each structure. These grounded parts include the structure members, clamps and armor rods. Also, since the ADSS is placed in the electric field of the energized phase conductors, significant induced voltages may be developed on the cable. This is important from the viewpoint of ADSS cable aging and safety of personnel working in the cable while the line remains energized.

As mentioned previously, the OPGW can be electrically bonded to the grounded structure or its grounding system, or it can be electrically insulated from the ground. In either case, however, the OPGW does not present new or unusual grounding problems.

Similar to OPGW, the WRAP aerial fiber optic cable can be electrically bonded to the grounded structure or it's grounding system, or it can be electrically insulated from ground. In either case, however, the WRAP aerial cable does not present new or unusual grounding problems as far as the cable itself is concerned.

Grounding of the communications equipment is discussed in a separate section.

2.3.7 Live Working

Installation and maintenance of the ADSS can be carried out live without interference to the power system, since the ADSS cable is typically installed a sufficient distance away from energized parts (i.e., maintaining minimum NESC clearances) and is normally more easily accessible from ground. Caution during live work is required to avoid potential hazards of induced voltages on metallic hardware of the ADSS that is not grounded. Also, some danger from leakage current may exist on heavily polluted ADSS. Experience shows, however, that such situations are rare.

OPGW aerial wires can be installed in the same way as normal ground wires unless otherwise stated by the manufacturer. As with normal ground wire, care should be taken to avoid scratching of aluminum coated strands to avoid corrosion. Some utilities have replaced regular ground wires with OPGW using helicopters without de-energizing the line, i.e., using live working procedures. Splicing of OPGW with the line energized can be performed. Splicing of the ground wire itself should follow the same procedures as for regular ground wire, i.e., electrical continuity of the ground wire must be maintained to avoid potentially hazardous voltage differences between disconnected ends. Handling and splicing of the fiber optic cable portion of the OPGW do not present additional dangers but require specialized training to ensure good performance of the spliced fibers.

Live work on WRAP fiber optic cables generally follows the same procedures and requires the same precautions and training as required for OPGW. In addition, care must be taken when clamping onto the ground wire to avoid breaking the fiber optic cable. An existing line can be retrofitted with WRAP fiber optic cable while energized. Specialized tools and machines are available to install the fiber optic cable on the existing ground wire without de-energizing the line. Splicing, however, is an easier operation since the ground wire and the fiber optic cable can be spliced separately.

2.3.8 Communication Equipment

Several general concerns exist regarding the use of low-voltage communications equipment in high voltage environments. The concerns relate to both, the operation of the equipment, and the safety of service personnel and the public.

Although the fibers themselves are immune to electric fields and interference from the power system, the electronic equipment may be susceptible to such influences. In addition, multiple grounded OPGW and WRAP aerial cables may result in ground loops which could contribute to interference problems, potential differences along ground connections and possible danger of equipment damage. These problems exist both during normal operation of the system and during abnormal situations such as faults, switching operations and lightning storms. Proper shielding of the communications equipment and proper coordination of grounding systems must be used to avoid these problems.

The issue of safety of service personnel and the public arises in situations when low-voltage power is brought from a distribution system to the vicinity of high-voltage power lines to operate the electronic equipment. A fault or a switching surge on the high-voltage line may induce very high voltages in the low-voltage supply system. This can cause damage to the equipment and also present a hazard to nearby humans. In addition, concerns exist that the fault current flowing to ground in situations of high tower footing impedance can raise the potential of the local ground (GPR) to hazardous levels. If the low-voltage supply system is also grounded at the fault location, the GPR can be transferred long distances through the low-voltage neutral (Transferred Potential) into the distribution system and into residences. Experience has shown that these situations are rare, but can be very hazardous, leading to electrocution and residential fires, when they occur. At this time, no obvious solutions can be suggested.

2.3.9 Summary Evaluation

A summary of pertinent electrical considerations in using ADSS, OPGW, and WRAP aerial cables in high voltage corridors is provided in Table 2-3. The relative importance of each, estimated based on an extensive literature search, is also indicated.

Table 2-3
Electrical Considerations Summary Evaluation

Consideration	OPGW		WRAP (on ground wire)		ADSS	
	Relative Importance	Comments	Relative Importance	Comments	Relative Importance	Comments
Placement on structure	Low	The OPGW is placed in the normal location of regular ground wires.	Low	The cable is placed in the normal location of regular ground wires.	Very high	Numerous ADSS cable failures observed caused by corona and dry-band arcing. Typically, failures occur within 2 to 12 months of installation.
Electric field analysis	Low	The OPGW is placed in the normal location of regular ground wires.	Low	The cable is placed in the normal location of regular ground wires.	Very high	Catastrophic failures have been experienced due to high electric field phenomena (corona).
Corona	Low	The OPGW is placed in the normal location of regular ground wires.	Low	The cable is placed in the normal location of regular ground wires.	Very high	Catastrophic failures (fiber optic cable damage and drop) have been experienced due to corona at armor rod tips.
Insulation	Low	The OPGW is placed in the normal location of regular ground wires.	Low	The cable is placed in the normal location of regular ground wires.	Very high	Catastrophic failures have been experienced due to corona damage to cable insulation.
Lightning performance	High	Failures have been reported due to lightning current heating.	High	Failures have been reported due to lightning current heating.	Medium	ADSS cable is normally installed below phases, hence shielded from direct lightning effects.

Table 2-3 (continued)
Electrical Considerations Summary Evaluation

Consideration	OPGW		WRAP (on ground wire)		ADSS	
	Relative Importance	Comments	Relative Importance	Comments	Relative Importance	Comments
Grounding	Low	The OPGW is placed in the normal location of regular ground wires.	Low	The cable is placed in the normal location of regular ground wires.	Very high	Improper grounding strategies may result in high electric field stresses and lead to ADSS cable damage.
Live working	Low	The OPGW is placed in the normal location of regular ground wires.	Medium	Care needed to avoid damaging the fiber optic cable when installing connections on the ground wire (for example, temporary grounds) .	Medium	Possible danger due to: induced voltages, leakage currents along polluted ADSS cable, lack of well-defined ground or reference potential in mid-span locations.
Communications equipment	Medium	Possible problems with Ground Potential Rise cause by lightning induced flashovers.	Medium	Possible problems with Ground Potential Rise cause by lightning induced flashovers.	Very high	Possible danger due to: induced voltages, leakage currents along polluted ADSS cable, lack of well-defined ground or reference potential in mid-span locations. Also, possible dangers when non-utility or workers not trained in live working are allowed to service equipment in the high voltage environment.

2.4 Mechanical Considerations

2.4.1 Placement

The location of an ADSS or OPGW aerial cable, based on mechanical considerations, must be selected to permit adequate clearances from the other phase and ground conductors to avoid any mid-span clashing of the aerial optical cables with the phase conductors and/or ground wires. The initial planning process requires that a decision is made regarding the fixing point of the cable on each tower of the system. The actual support point should be chosen after an evaluation of the following issues:

- Ground clearances and phase-to-phase clearance requirements must be maintained during installation (i.e., for live working) and inspection and maintenance related tasks (i.e., again for live working).
- Mechanical clearances to phase conductors and/or ground wires need to be maintained during blow-out and ice induced galloping.
- The additional loading imposed on support structures and the availability of suitable attachment points.
- Required Shielding Angle

2.4.2 Structural Loads

The 'lateral swing' characteristics of the ADSS aerial cable varies substantially from behavior observed for metallic conductors. Due to the small weight and relatively large diameter of optical fiber aerial cables any transverse wind will result in a wide deflection angle of the cable. For a normalized wind of 30 m/sec (98.4 ft/sec) the deflection angle of an optical fiber aerial cable can reach up to about 80 degrees. Comparable phase conductors or optical fiber cables with metallic armor reach deflection angles of about 40 to 45 degrees only. Consequently, this fundamentally different behavior of ADSS aerial cables with respect to phase conductors must be considered when placing them on a tangent tower in a high voltage corridor.

Another problem that must be considered when installing an ADSS aerial cable is the behavior under different climatic conditions. Due to the small weight to diameter ratio, together with a relatively low Young's modulus, an elongation up to 0.6 % of the ADSS aerial cable can result under ice load conditions (103). Phase conductors have an elongation in the range of 0.1 % under the same conditions. This means, that an ADSS optical fiber aerial cable must be placed under high tension and therefore low sag under normal conditions to maintain an appropriate distance to ground under ice loading conditions.

2.4.3 Mechanical Modeling and Analysis

Creep rates for ADSS fiber optic cables are significantly different that comparable values observed for traditional phase conductors and ground wires. A creep strain of approximately 0.1 % can be expected after 30 years (i.e., if strung at a constant 50 % of UTS), which is well below the value observed on conventional metal armored cables. However, it should be kept in mind that creep rates may be significantly higher if ADSS tensions increase frequently as a result of ice or snow deposits.

Generally, sag-tension charts are developed for various span lengths at a number of temperatures for varying load cases. Each span is usually considered separately and the aerial cable or wire is assumed to be at its final operating condition. Required parameters to calculate sag-tension characteristics of ADSS and OPGW aerial cables and wires are the respective cross-sectional areas of each material, the Young's Modulus of Elasticity of each component, and the Coefficient of Expansion of each material. For example, the Coefficient of Expansion of Aramide, Copper, and Steel is approximately $-2.0 \cdot 10^{-6}$/°C, $17.0 \cdot 10^{-6}$/°C, and $12.0 \cdot 10^{-6}$/°C ($-3.6 \cdot 10^{-6}$/°F, $30.6 \cdot 10^{-6}$/°F, and $21.6 \cdot 10^{-6}$/°F), respectively. The Coefficient of Expansion of the composite cable or wire is usually approximated based on the values of each of the materials used in the construction of the aerial cable or wire. Consequently, each type of aerial cable or wire has a different Coefficient of Expansion.

Sag and tension can then be calculated using either the parabolic approximation or the more accurate catenary formulation for a suspended cable or wire. While the parabolic approximation is typically sufficiently accurate to perform a feasibility study or preliminary design, it is recommended to calculate sag and tensions using the catenary formulation for the final design. Sag-tension charts based on the catenary formulation can usually be obtained from the manufacturer and are commonly treated confidential.

2.4.4 Cable and Wire Blow-Out

ADSS cables are very light and, as a result, in high winds the plane of the catenary can become nearly horizontal, making clearance to phase conductors an important consideration. Additionally, the sag difference between every day and maximum working tensions may be greater than the adjacent conductors. Consequently, it is necessary to consider sag, tension, and clearance-to-ground limits during all weather conditions in the selection of the suspension tower attachment point.

2.4.5 Aeolian Vibration

OPGW performance evaluations under aeolian vibration are an important consideration. For normal ACSR conductors, the maximum peak-to-peak anti-node vibration amplitudes are on the order of the conductor diameter. However, significantly higher vibration amplitudes can be observed on OPGW fiber optic wire installations. The higher vibration amplitudes are commonly attributed to lower unit mass (i.e., aluminum construction) and lower self-damping (i.e., solid or hollow tube core construction) of the ADSS cable.

Aeolian vibration fatigue tests (23, 51, 73, 95) on a limited number of OPGW fiber optic wires have been performed for up to 10^8 cycles at frequencies of 36 Hz with bending strains of +/- 150 micro-strain. OPGW fiber optic wire tensions in these limited tests were held constant at 20 % of the conductor's ultimate strength. Results showed no breakage of optical fibers or significant signal attenuation during any of the tests. Dissection of the conductor revealed no wire breaks and only minimal wear on the wires and on the alloy tube in the area of the suspension clamp. However, of ten armor rod strands, four had fractured at the suspension clamp. Although this reduces the subsequent protection that the armor rods extend to the composite conductor it is commonly concluded that 10^8 cycles are representative of a reasonable life for such a component. For example, if the component vibrates at 2 Hz, the expected life of the component equals approximately 1.6 years.

The self damping characteristics of the OPGW wires are adequate to keep the micro-strain below +/- 150 at higher frequencies (i.e., more than 90 Hz). However, additional damping may be required at the lower frequencies. For excessive aeolian vibration, dampers attached to each span typically provide sufficient damping to minimize the risk of fatigue failures. While the normal 'Stockbridge' damper has been adopted for OPGW aerial cables and optical phase conductors, a rigid plastic helical configuration is used for ADSS cables. For ADSS cables it is important that the damper is fitted tightly to the cable to prevent it from working loose and sliding along the cable.

Currently there is little known about the vibration tendencies of ADSS, OPGW, and WRAP type fiber optic cables and only limited field studies have been performed to evaluate the aeolian vibration performance of these cables. Based on limited data (23, 51, 73, 95), it appears that similar to traditional conductors and ground wires the vibration severity increases as the tension increases. However, at present, endurance limits for ADSS, OPGW, and WRAP cables have not been identified. Therefore, it is not clear at which point fatigue and failure will occur. It is estimated that steel or aluminum cables exposed to vibration levels would experience fatigue failures within 10 years which is of course substantially less than the typically expected service life of 25 years.

2.4.6 Galloping

Sag-tension analyses are typically used to calculate and plot the galloping ellipses for ADSS and OPGW aerial cables. A plot of the galloping ellipses displays the clearances required to avoid flashover during galloping. Galloping ellipses of ADSS cables differ significantly from ellipses predicted for comparable phase conductors and ground wires (50, 53, 62). It is estimated that the galloping ellipses of ADSS aerial cable are significantly smaller than for traditional ground wire and phase conductors. Consequently, it is recommended to further study the phenomena and define the dynamic behavior of ADSS fiber optic aerial cables more accurately.

The galloping ellipse design method, traditionally used for phase conductors and shield wires, is based upon observed behavior of actual galloping events on transmission lines over many years. However, manufacturers of ADSS cable claim that the propensity of ADSS aerial cable to galloping is significantly lower than for traditional phase conductors and ground wires. Nevertheless, lacking any more detailed information, the galloping behavior of ADSS cables is commonly assumed to be comparable to traditional wires (i.e., conservative assumption).

2.4.7 Summary Evaluation

A summary of pertinent mechanical considerations in using ADSS, OPGW, and WRAP aerial cables in high voltage corridors is provided in Table 2-4. The relative importance of each, estimated based on an extensive literature search, is also indicated.

Table 2-4
Mechanical Considerations Summary Evaluation

Consideration	OPGW		WRAP (on ground wire)		ADSS	
	Relative Importance	Comments	Relative Importance	Comments	Relative Importance	Comments
Placement	Low	The OPGW is placed in the normal location of regular ground wires.	Medium	The cable is wrapped around the ground wire or phase conductor.	High	Placement on support structure is critical. Requires an evaluation of member strength.
Structural Loads	Low	Larger diameter OPGW likely to increase loads on support structures.	Medium	Larger diameter due to WRAP likely to increase loads on support structures.	High	Placement on support structure is critical. Requires an evaluation of member strength.
Mechanical Modeling and Analysis	Medium	Creep and sag-tension relationships differ somewhat from traditional phase conductors and ground wires.	Medium	Modeling and analysis of interaction between wrapped cable and conductor is difficult.	High	Creep and sag-tension relationships differ significantly from traditional phase conductors and ground wires.
Cable and Wire Blow-Out	Low	The characteristics of the OPGW are similar to values observed for traditional ground wires and phase conductors.	Medium	The increased drag exerts a noticeable influence on the wrapped ground wire or phase conductor.	High	Blow-Out values of ADSS cables are significantly larger than for traditional phase conductors or ground wires.
Aeolian Vibration	Medium	Self-damping values of OPGW are noticeably different from values for conductors.	Low	Self-damping of wrapped cables not significantly different from values for conductors.	High	Self-damping of ADSS significantly smaller than values for conductors.
Galloping	Low	OPGW galloping characteristics are very similar to values observed for conductors.	Low	Galloping of wrapped cables observed to be negligible as a result of construction.	High	Galloping behavior of ADSS cables differs significantly from conductors. Use of conductor ellipses is very conservative.

2.5 Installation

A number of issues need to be addressed prior to the installation of aerial cables or wires in high voltage corridors. First, route maps are typically procured that include information on terrain features, elevations, and access points. Second, it is necessary to identify the different types of towers on the route and associated drawings. Third, a site survey should be completed (i.e., unless current site survey available) and splice points should be identified.

OPGW aerial wires can be installed on an energized circuit. Great care should be taken to utilize similar methods (i.e., energized or non-energized work procedures) to those typically used in the stringing of regular ground wire. Also, equipment such as stringing blocks typically used for the stringing of OPGW aerial wires should be sized adequately to be used in the installation of OPGW.

Prior to installation, training should be provided for the installation crews. Specific installation details should be provided for each phase of the installation to ensure that the expected optical performance of the fiber will not be compromised in the installation process. Finally, optical cable or wire should not be allowed to rotate during the installation because it will allow the stranding to loosen up causing the wire to elongate. Providing two alternating layers of reinforcement or stranding can significantly reduce the tendency to rotate.

Because ADSS cables are completely non-metallic, they can be installed on energized circuits. This is an important feature since it helps reduce installation costs by avoiding or minimizing loss of revenue during the installation period. A safe and viable code of practice in the installation that can be followed includes: a) the ADSS cable and rope pulling connection must be light and flexible in addition to being non-metallic and be suitable for use near the voltage rating of the energized conductors; b) installation equipment such as tensioning gear must be functional and calibrated wherever applicable; c) adequate working clearances to adjacent live circuits must be maintained; d) all erection equipment must be fully insulated; e) line fittings and vibration dampers should have temporary ground leads attached to provide a low resistance path to the ground for any induced currents; f) line crews should be provided with on-site training to validate erection equipment and working methods.

Our review showed that OPGW is mainly used for long span, high voltage applications and that the deadend fittings used on OPGW wires are primarily of the bolted block or helical grip type. Typically, the suspension hardware used for OPGW fiber optics are either armor grip suspension or bolted clamps while dampers are mostly of the Stockbridge type. In the past, ADSS cable appears to have been used mainly for shorter spans and lower voltages (7), but recently, ADSS cable with span lengths of up to 1000m is being installed on 500-kV transmission lines. Contrary to OPGW, ADSS deadend fittings are mostly of the helical type and the fiber optic cable is suspended by armor grip suspensions. Also, the dampers used on ADSS cables are almost exclusively spiral vibration dampers.

For OPGW conductors with two or more layers of strands, whether installing by tension stringing or slack pulling methods no additional precautions are required beyond those normally associated with good practice in the handling and erection of conductors for high voltage lines. For OPGW with a single layer of strands there is a tendency to unwind during tension stringing, with a consequent increase in length that reduces the value of the designed strain margin. Therefore, procedures must be adopted to restrain this tendency by utilizing an anti-rotational device at the leading end of the conductor. This in turn will require the use of open-sided running blocks. Additionally, the arrangement for terminating the conductor at tension towers must restrain the conductor's tendency to untwist.

In optical fiber transmission lines, one of the most important considerations is how splicing operations can be simplified and how the time for such splicing can be shortened to reduce installation cost. A number of aerial fiber optic connectors have been designed in the recent past and evaluated in limited field installations. Based on the evaluation it appears that significant cost savings can be achieved.

WRAP fiber optic cables are typically easy to install even in relatively difficult terrain and eliminate the need for guard structures to avoid obstructions such as power lines, railways, and roads. At the same time, the universal applicability of the WRAP installation process easily facilitates shield wires and conductors of varying size which reduces procurement and inventory cost. However, the WRAP type cable must have the right combination of strength and flexibility to be installed at the correct tension. Also, the added projected area can reduce the allowable wind span by up to 20 percent. Furthermore, good tracking and heat resistance are an important consideration to ensure that a WRAP cable can resist temperatures in excess of 100°C (212°C) caused by a lightning strike or fault current in the conductor.

The installation of WRAP type cables is usually done by a cable wrapping machine that spins a cable reel as it travels along the conductor or shield wire. It is important that the cable wrapping machine is fitted with a counter-balance system that keeps the machine in balance along the span as the optical cable is dispensed. Additionally, it is critical that the cable tension control system of the wrapping machine is capable of maintaining the correct tension even on steep inclines and declines.

Typically 40 km (25 miles) or greater repeater spacing is achievable with single-mode fiber, which is less expensive than multi-mode fiber, operating at 1300 nm. The repeater spacing can be readily extended if the single-mode fibers are operated at 1550 nm, for which the attenuation of the installed fiber typically does not exceed 0.3 dB/km (0.48 dB/mile). The maximum repeater spacing for multi-mode fiber ranges from 7.5

km (4.7 miles) to 25 km (15.5 miles) for wavebands ranging from 850 to 1300 nm respectively at a nominal rate of 34 Mbit/s.

2.5.1 Equipment

Fiber optic aerial cable and wire are normally supplied on either wooden or metal reels. The type and construction of the reel stand determine the methods and tools required for handling. Reels must be supporting by either an axle or from above with the help of a spreader bar. The stand has to have a tensioner to supply the required back tension to the aerial cable. The stand should be selected to accommodate the cable reel dimensions and gross weight. Some standard reels are not designed to withstand the forces developed by braking during high tension stringing operations. Consequently, direct tension stringing from the reel at aerial cable installation stringing tensions should not be attempted unless the stand and reel has been designed appropriately. However, the cable may be pulled directly from the reel stand if slack stringing methods are used that allow only minimal tension to be applied.

Both, bullwheel and reel type pulling machines can be used to install fiber optic cable. However, the pulling and braking system should be operated smoothly to prevent any sudden jerking or bouncing of the cable during the installation. Pullers and tensioners should be equipped with tension indicating and limiting devices to prevent any overstress in the aerial cable. Reels are typically stored in the same manner and environment considered appropriate for conductor and ground wire reels.

Equipment used in the installation such as sheaves should be dimensioned in such a manner that the diameter of the sheave is not less than 0.3 m (12 inches) at mid-span suspension points and 0.5 m (20 inches) at angles in excess of 25 degrees. The minimum radius and depth of the sheave groove is recommended to be 75 percent larger and 25 percent deeper than the diameter of the cable, respectively.

2.5.2 Tensioning and Pulling Requirements

Mechanical strength and bending behavior are important issues in the evaluation of cable alternatives. In order to avoid breaking of the fiber under normal operating conditions it is necessary that the cable has passed a quality control screening test of at least 5 N (1.1 lbs). This means that the whole fiber has been exposed to a force of 5 N (1.1 lbs) so that small flaws and defects in the primary coating are detected by a breakage of the fiber. This screen test together with a normal fiber strength of more than 50 N (11.25 lbs) for a 1 m (3.3 ft) sample gives the security that is necessary for optical fiber cables.

Pulling rates of 1.5 to 8 km/hr (1 to 5 miles/hour) allow the cable to pass through the sheaves smoothly. Once the cable has started to move, the progress should be maintained at a constant rate until the whole cable segment has been pulled into place.

At all times during the pull, the operator of the tensioner should monitor the tension measured in the cable to assure that the maximum pulling tension is not exceeded. Generally, the pulling tension of the cable should never exceed 50 percent of the maximum initial sagging tension.

2.5.3 Pulling Lengths

The selection of pull, tension, anchor, and splicing sites involves many factors ranging from system design issues to logistics and equipment capabilities. Segment lengths are governed by the allowable number of splices, accessibility, obstacles in the right-of-way, and cable reel lengths. Other factors that are critical are the maximum load the aerial cable or wire can handle, maximum permissible structural loads, and the availability of adequate grounding systems wherever necessary. Installations of ADSS or OPGW aerial cable or wire use pulling lengths ranging from 2 to 5 km (1 to 3 miles) depending on the weight and diameter of the cable to be installed.

2.5.4 Installation Methods

The installation of ADSS or OPGW aerial cables normally requires ground access along the power line, even though tension stringing techniques are generally used. Suitable running blocks are suspended from the attachment points. The type of running blocks to be used is usually recommended by the manufacturer. A pilot rope is then manually installed through the running blocks between the first and the last tower of the stringing section. The puller and tensioner should be positioned in such a manner that the slope from the equipment to the first tower does not damage the cable during the installation. Additionally, it is recommended to use a large block at the first structure to minimize the bending stresses in the cable during installation.

The pulling winch and back tensioner are positioned at the first and last tower, respectively. These are then used to install the ADSS or OPGW aerial cable, which is connected to the pilot rope. At the same time, the ADSS or OPGW drum is located at the back tensioner to supply sufficient back tension to keep the wire clear of the ground and other obstructions. Once the aerial cable has been pulled in place, the tension in the wire is adjusted to achieve the correct sag-tension parameters. The aerial cable is then clamped off at the end of the first tension section and the process is repeated down the line.

More recently, electric utilities have developed methods for installing ADSS or OPGW aerial cables on multiple circuit overhead power lines without taking an outage on adjacent circuits. These methods usually employ helicopters and cradle blocks. Typically, the aerial cable is pulled using a previously installed light rope at low tension. The advantages of this method of installation are that there is no need for circuit outages and the effects of roads, railways, low voltage lines and other obstructions are minimized.

Experience with stringing ground and phase wires indicates that significant induced currents (as high as 500 A) can occur when stringing is performed near other energized lines (23, 103, 111). Hence, stringing of OPGW and WRAP cables live (i.e., when the line is energized) needs to recognize this hazard and suitable precautions need to be taken. The precautions normally include the use of "running grounds", i.e., roller assemblies that allow the cable being strung to pass through well-grounded rollers under sufficient tension to maintain good continuous contact. The running ground assemblies are grounded to structure steel and/or driven ground rods. Depending on the section length of the cable being strung, the running grounds may need to be placed in several locations, i.e., at the bullwheel and on several towers along the line.

The use of running grounds on the OPGW is the same as for regular ground wires. However, the WRAP cable presents the problem of continuity of contact to the ground wire. Since the optical cable is wrapped around the ground wire, a traditional set of rollers cannot provide continuous reliable contact, because the rollers must "jump over" the non-conductive fiber optic cable. Modified roller assemblies, which allow the contact rollers to rotate around the periphery of the WRAP cable, can be utilized. This problem, however, pertains only to the stringing of WRAP cable.

When retrofitting an existing cable by wrapping the fiber optic cable on the existing (i.e., already strung) ground wire, the problem of induced current is not an issue. The fiber optic installation is performed by an automated device that is installed on the ground wire and rides along it in a spiral fashion to wrap the fiber optic cable stored on-board the device. In this case, caution needs to be exercised by workers when installing and removing the device on the ground wire, but this procedure does not require additional safety related considerations beyond those already known and needed during traditional live work.

Safety equipment for use in stringing operations is addressed in IEC Publication 1328 TR2 Ed.1 (1995) *Live working - Installation of transmission line conductors and earthwires - Stringing equipment and accessory items*, and document 78/186/CD *Live working - Installation of distribution line conductors - Stringing equipment and accessory items* and in IEEE Standard 524-1992 *IEEE Guide for the Installation of Overhead Transmission Line Conductors*.

Installation of ADSS presents its own set of safety considerations. Since the ADSS is not conductive, the issue of induced current is eliminated. Two other issues arise, however:

- Handling and installation of metallic hardware in the vicinity of live lines.
- Training of workers in fiber optics and live working.

These two issues require totally dissimilar skills and training, but they are brought together during installation of ADSS on energized lines. At this time, the workers are typically trained in one or the other, but not both. Often, in fact, the optical work is the specialty of communications workers while live installation skills are available in the operations and maintenance groups.

To resolve this dichotomy of requirements, utilities may wish to invest in training special crews to perform both functions, or to control very strictly the activities and access of the two groups. For example, one utility utilized maintenance crews skilled in live working to install the cables on structures under live conditions, and at the same time restrict the communications workers from approaching the structures. After the structure work is completed, the communications workers take over and perform the required connections to the cables on the ground. No guidelines or standards, other than those developed within individual organizations based on common sense, have been formulated to date regarding the live installation of ADSS.

2.5.5 Summary Evaluation

A summary of pertinent considerations for installing ADSS, OPGW, and WRAP aerial cables in high voltage corridors is provided in Table 2-5. The relative importance of each, estimated based on an extensive literature search, is also indicated.

Table 2-5
Installation Considerations Summary Evaluation

Consideration	OPGW		WRAP (on ground wire)		ADSS	
	Relative Importance	**Comments**	**Relative Importance**	**Comments**	**Relative Importance**	**Comments**
Equipment	Low	Equipment used for OPGW installations is very similar to traditional conductor stringing equipment.	High	Equipment used for installation of wrapped cable is very critical to achieve correct level of snugness.	Medium	Installation of ADSS requires training and high level of quality control in addition to some specialized equipment.
Tensioning and Pulling Requirements	Low	Standard methods used in installation.	Medium	Requires specialized self-propelled tensioner for steep up and down slopes.	Low	Standard methods used in installation.
Pulling Length	Low	Standard pulling lengths limited by reel size and line geometry.	Medium	Standard pulling lengths limited by reel size and line geometry.	Low	Standard pulling lengths limited by reel size and line geometry.
Installation Methods	Low	Standard ground or helicopter installation methods for outage and live working.	High	Helicopter installation difficult and installation typically time consuming. Potential for personnel hazards in high voltage installations.	High	Standard ground or helicopter installation methods for outage and live working. Potential for personnel hazards in high voltage installations.

2.6 Inspection and Maintenance

Fiber optic system supervision is typically dealt with on two different levels. A lowering of the transmission quality in the fiber optic communication constitutes a minor problem, while the loss of transmission capability requires immediate remedial action by the operator of the system. Transmission characteristics of the optical fiber and terminal equipment that are usually monitored are:

- End to End Power Loss
- Attenuation in Optical Fiber
- Attenuation at Splices and/or Connectors
- Multiplexer Characteristics

The electrical safety issues during inspection and maintenance relate also to the fact that the operations often bring together two previously unrelated technologies and skill sets:

- Fiber optic technology
- Live working technology

As mentioned in connection with installation of the OPGW, WRAP and ADSS cables, communications workers are typically not trained in live working procedures, and live working crews are not skilled in handling delicate fiber optic cables, equipment and components. No guidelines or standards, other than those developed within individual organizations based on common sense, have been formulated to date regarding the live inspection and maintenance of fiber optic installations.

2.6.1 Types of Failures

In general, operating experience for all types of fiber optic cable and any associated hardware has been good. However, some minor problems have been reported with all cable types and fittings. The share of major problems experienced with fiber optic cable is higher for ADSS and WRAP than for OPGW. Most of the major problems associated with ADSS cable at lower circuit voltages appear to be related to galloping, damage of the cable sheath from bird pecking, and broken fibers. Most of the major problems associated with ADSS cable at higher circuit voltages are similar to the problems mentioned previously with the inclusion of corona cutting, tracking and arcing.

The outdoor performance of fiber optic cable sheaths is affected by a number of different influences including ultraviolet light, atmospheric oxygen, moisture, and gaseous and solid pollution. Typically, assuming the cable is initially satisfactory, long-term outdoor exposure may result in one or more of the following adverse effects: a) changes in the molecular weight of the polymer and modifications of the polymer by oxidation; b) leaching of plasticizers resulting in embrittlement and possible cracking of the sheath; and c) leaching and modification of the additives and/or filler materials. The contributing factors to the degradation are: a) weather (i.e., sun, rain, climate); b) pollution (i.e., sand, dust, salt, industrial); c) thermal (i.e., temperature changes); and d) mechanical (i.e., wind, snow, ice).

2.6.2 Aging Effects

The attenuation stability of optical fibers integrated in ADSS, OPGW, and WRAP cable over time and temperature is of paramount importance to the planning of long distance communication links. However, currently there are no acceptance tests that enable a utility to qualify a minimum level of performance. Tests have shown that some form of aging process is taking place on the fibers that increases attenuation in the fibers over time (12, 18, 23). To account for the increase in attenuation over time it has been suggested that a safety margin of not less than 0.01 dB/km (0.02 dB/mile) should be used. However, experimental data are very limited and may differ significantly for cables other than the specimens tested.

Fiber strain in any optical cable or wire must be carefully controlled because it affects the expected service life of the optical fiber and system attenuation. To achieve an expected service life of 25 years, fiber strain must not exceed 1/3 of the proof strain applied during manufacture. Additionally, local radial crushing forces must be avoided by the design of the cable since they increase the local attenuation caused by microbending.

2.6.3 Inspection Methods and Tools

ADSS aerial cables require special safety precautions as a result of their possible semi-conducting nature. Special safety procedures and arrangements need to be defined to inspect ADSS aerial cables whenever working under live line conditions. While ADSS cables can be considered non-conducting during the installation in the presence of live lines (i.e., if regulations allow), ADSS is very likely to become semi-conductive during the service life as a result of surface deposits and the hydrophilic nature of the jacket material, which should be considered during maintenance.

Equipment required for inspection and maintenance for ADSS, OPGW, and WRAP aerial cables and wires is usually limited to technology that can be used to check for the integrity and degradation of the transmission in the fiber of the communication cable. Currently, there are no inspection tools (i.e., other than close-up visual examination) that can assist the electric utility to identify any potential electrical or mechanical problems of ADSS, OPGW, or WRAP aerial cables and wires prior to failure.

2.6.4 Repair Methods and Tools

Usually, an alarm indication of a broken fiber or change of light signature is required to identify a defect in any of the fibers (i.e., potential impending mechanical failure) of the aerial cable or wire. Consequently, an interruption (i.e., potential mechanical failure) of the transmission in the whole cable is usually indicated by the large number of fibers detected to be defective. However, as long as the number of undamaged fibers is above the number of used fibers, the repair can be planned but does not have to be performed immediately after recognition of the problem. The repair can therefore be delayed until other maintenance operations are required. On the other hand, if the communication system is using all available fiber, repairs must usually be performed without delay.

If the defect is located at a splice, the repair can usually be done with the remaining part of the optical cable in service. If the defect is located along the power line, it must usually be taken out of service to allow for the repair. A few mid-span joints have been recently developed by manufacturers but are not commonly used. Typically, a mid-span repair requires significant resources and a circuit outage which makes the cost of this technology prohibitive. Under these circumstances it is usually more effective to replace a section of cable at locations where splicing can be facilitated.

2.6.5 Summary Evaluation

A summary of pertinent considerations for the inspection and maintenance of ADSS, OPGW, and WRAP aerial cables in high voltage corridors is provided in Table 2-6. The relative importance of each, estimated based on an extensive literature search, is also indicated.

Table 2-6
Inspection and Maintenance Considerations Summary Evaluation

Consideration	OPGW		WRAP (on ground wire)		ADSS	
	Relative Importance	Comments	Relative Importance	Comments	Relative Importance	Comments
Types of Failure	Medium	Reduced self-damping increases likelihood of fatigue failures of strands. Suspension hardware design critical to service life.	Medium	Tension of wrapped cable is critical in maintaining position on strength member. Failures typically encountered as a result of electrical effects.	High	Numerous ADSS cable failures observed caused by corona and dry-band arcing. Typically, failures occur within 2 to 12 months of installation.
Aging Effects	Medium	Fiber service life significantly influenced by stress levels and presence of moisture. Aeolian vibration (no dampers) observed to limit service life.	Medium	Fiber service life significantly influenced by stress levels and presence of moisture. Service life affected by electrical environment.	High	Fiber service life significantly influenced by stress levels and presence of moisture. Service life affected by electrical environment.
Inspection Methods and Tools	High	Currently, there are no methods to economically detect strand breakage and related problems.	Medium	Methods need to be developed to detect corona and tracking.	High	Methods need to be developed to detect corona and tracking.
Repair Methods and Tools	Medium	OPGW mid-span splice technology currently not economical. Mid-span repairs require replacement of span segment.	Low	Mid-span repairs not problematic. Long term characteristics of splices should be evaluated.	Medium	ADSS mid-span splice technology currently not economical. Mid-span repairs require replacement of span segment.

3

CONCLUSIONS AND RECOMMENDATIONS

Primarily, there are three different cable options available to an electric utility that elects to integrate communications into their existing power transmission system. The currently available cables and wires that can be used in high voltage corridors are:

- ADSS (All-Dielectric Self Supporting Cable)
- OPGW (Optical Ground Wire)
- WRAP (Optical Cable Wrapped on Ground Wire)

Typical material and installation cost are shown in Table 2-1 for aerial cable or wire with either 24 or 48 optical fibers. The cost of the cable/wire itself and the labor required in the installation make up the majority of the system development cost.

There has been considerable experience gained with successful OPGW applications in power transmission corridors at most system voltages. For the most part, with the exception of aeolian vibration problems, the installation and operation of OPGW aerial wires has been satisfactory. The application of WRAP cable, although less common than OPGW, has also been relatively successful. The challenges that have not been fully resolved yet on WRAP cable include maintaining tension during stringing, control of contact between the WRAP cable and grounded parts to eliminate induced currents, and proper application of ground wire clamps to avoid damage to the optical cable during live work. However, recent applications of ADSS aerial fiber optic cables have shown that there are a number of technical challenges that remain to be solved to achieve an acceptable service life.

Inspection and damage assessment tools need to be identified to evaluate the integrity of aerial cables and wires. These inspection and assessment tools are required by electric utilities to locate developing problem areas prior to catastrophic failure. According to some estimates, service interruption of a fully loaded fiber optic cable or wire can cause the affected carrier losses of up to $1000 per minute. Regular inspection and reliable damage detection procedures and tools could be used in preventive maintenance programs that could significantly reduce repair cost and increase the reliability of the communication system.

Currently, there are no IEEE standards or guidelines that assist the utility engineer in the planning, installation, operation, and maintenance of fiber optic communication systems in high voltage corridors. Existing standards and draft standards currently in existence or under development solely address electrical and mechanical performance of aerial cables that are mostly suited for quality control in the manufacturing process.

3.1 All Dielectric Self-Supporting (ADSS) Cables

ADSS aerial cables exhibit significantly different creep behavior than traditional phase or ground conductors. ADSS cables frequently subjected to icing may creep substantially more than traditional wires that are likely to reduce the service life of the communication system. Thus, it is recommended to investigate the stress-strain, creep, and sag-tension characteristics of commonly used ADSS aerial cables to define the long term performance and expected service life under various field conditions. The results of such an investigation would allow utility engineers to more accurately define system capital cost and inspection and maintenance requirements.

Further research is required to more accurately define the aging mechanism and service life of ADSS aerial cable in the presence of electric fields and ultra-violet (UV) radiation. It appears that the presence of UV radiation in combination with various pollutants can significantly accelerate the aging process of ADSS aerial cable resulting in a significantly shortened service life. Our estimates, at this time, indicate that the service life of ADSS aerial cables under adverse conditions may be as short as 7 to 10 years rather than the anticipated service life of 20 to 30 years.

It has been determined that the severity of aeolian vibration is proportional to the tension in the cable. It appears that the level of vibration increases as the tension of ADSS cable increases. Consequently, for most applications, it is necessary to employ dampers on ADSS cables for virtually any length of span. Currently, there are a number of areas that have not yet been clearly defined. These areas are:

- Fatigue Endurance Limits
- Self-Damping
- Damper Performance
- Effects of Hardware
- Effects of Marker Balls

It is recommended that more independent research in this area should be conducted to provide electric utilities with the information required to mitigate potential system problems.

Currently, there are indications that the galloping behavior of ADSS aerial cables may be significantly different from the galloping behavior of traditional conductors. The prediction of galloping amplitude, galloping ellipse, and dynamic loads for traditional conductors is currently based on a very limited number of observations made on transmission lines in the 1960s. Limited tests indicate that the galloping ellipses of ADSS aerial cables may be significantly smaller than predicted which would allow the utility engineer to more accurately define placement locations within the right-of-way. More data are required to accurately predict:

- Galloping Amplitude
- Galloping Motion
- Resulting Dynamic Loads

It is recommended that more independent research in this area should be conducted to provide electric utilities with the information required to mitigate potential system problems.

The location of an ADSS cable must be selected to permit adequate clearances from the phase and ground conductors and to minimize the electric potential on the sheath. It has been argued that capacitively induced voltages drive currents along the contaminated cable sheath causing dry band arcing and eventual thermally induced damage to the cable sheath. Other damage mechanisms include degradation of the ADSS cable by corona activities at the tips of armor rods and other hardware, and corona on water droplets under wet conditions. Indications are that non-metallic hardware could be utilized to mitigate some of the electric field problems. More detailed studies need to be performed to further evaluate the effectiveness of such hardware before field installation.

Field density or voltage level thresholds that cause damage to ADSS aerial cables have not been clearly defined. Similarly, threshold levels have not yet been correlated with rates of degradation and associated changes in the service life. Further research is required to more accurately define maximum permissible exposure levels and associated service lives. Additional information in this area will allow the utility engineer to more accurately define placement positions in existing right-of-ways, evaluate the potential for sheath damage and eventual mechanical failure of the aerial cable, and to evaluate life cycle capital cost of the communication link.

ADSS aerial cables require special safety precautions as a result of their possible semi-conducting nature. Special safety procedures and arrangements need to be researched and defined to inspect ADSS aerial cables whenever working under live line conditions. Experience shows that ADSS aerial cables are very likely to become semi-conductive during the service life as a result of surface deposits and the hydrophilic nature of the jacket material, and this should be considered during maintenance.

3.2 Optical Ground Wire (OPGW)

The severity of aeolian vibrations on OPGW aerial wires is proportional to the tension in the wire. Limited tests show that the self-damping and fatigue endurance limits of OPGW aerial wires are noticeably different from comparable values for traditional conductors. Consequently, for most applications, it is necessary to employ dampers on OPGW cables for virtually any length of span. Similar to ADSS fiber optic cables, there are a number of areas that have not yet been clearly defined. These areas are:

- Fatigue Endurance Limits
- Self-Damping
- Damper Performance
- Effects of Hardware
- Effects of Marker Balls

Consequently, it is recommended that more independent research in this area should be conducted to provide electric utilities with the information required to mitigate potential system problems.

3.3 Wrap-Type Fiber Optic Cables (WRAP)

WRAP aerial cables are most frequently attached to the ground wire. The main problems with this type of cable currently encountered are related to the tension maintained during the installation process. Based on field experience, it is critical to maintain the 'correct' tension at all times during the installation. However, currently there are no clear guidelines addressing the magnitude of the tension and or the consequences if the tension can not be maintained correctly. More field experiences should be identified to better define the long term performance of this technology.

Similar to ADSS aerial cables, there are indications that the galloping behavior of WRAP aerial cables may be significantly different from the galloping behavior of traditional conductors. Limited tests indicate that the galloping characteristics of WRAP aerial cables may be significantly different from predicted behavior. More research should be performed to accurately define:

- Galloping Amplitude
- Galloping Motion
- Resulting Dynamic Loads

High temperature conductor operation can result in excessive WRAP tensions when the aerial cable is installed on the phase conductor. Indications are that this may cause premature failure of the optical fibers resulting in a complete loss of communications. Further studies are necessary to identify acceptable combinations of initial wrapping tensions and temperature changes that do not adversely affect the integrity of the optical fibers.

4

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