Operational and Safety Improvements to OCS with Non-conducting Span Wire

Paul F. White
HNTB, Inc.
Chelmsford, MA

Andrew J. Gillespie, P.E.
Southeastern Pennsylvania
Transportation Authority
Philadelphia, PA

ABSTRACT

To improve operational reliability and safety on its light rail and trolley bus systems, the Southeastern Pennsylvania Transportation Authority (SEPTA) instituted a program of replacing old steel span wires with a superior type of non-conducting wire for the suspension of overhead contact systems (OCS). The trolley wire which provides power to SEPTA's light rail vehicles (trolleys) and trolley buses is energized at 600 volts direct current and must have multiple insulators when attached to steel span wires. Broken insulators can cause the trolley wire to short circuit and burn down causing severe delays to service. Broken span wires from dewired trolley poles may lay across the trolley wires and hang down onto the street energized causing power outages or danger to pedestrians. New non-conducting span wire (synthetic rope referred to as span rope) prevents accidental energizing and short circuit power failures while providing a high measure of safety to installation crews and the general public.

Span wires in general use on transit systems in North America use a stranded steel or bronze wire that is prone to frequent and complete failure when struck hard by a dewired trolley pole. The fallen wires often become energized and lay on the street "alive" placing pedestrians at risk to electrocution. Installation and repair line crews must use extreme caution when running new steel span wires over or around the energized trolley wire because they are conductive and can short to ground causing an electrical explosion. Using the new span rope, line crews are free to install it quickly and without regard for it short circuiting. This has created an air of confidence amongst crew members and has allowed them to work on the OCS while energized with safety and efficiency.

In this paper an explanation of the operational and maintenance problems encountered with steel stranded span wires is presented and how the new span rope has solved these problems. The technical reasons why the new span rope is advantageous and how it has been implemented is also discussed. It further explains how introduction and adoption of this wire has improved employee efficiency and how SEPTA has worked towards improving the safety of personnel and the public. Introduction and use of non-conducting span wire has improved the SEPTA OCS system in operation, maintenance, cost and safety.

INTRODUCTION

The SEPTA light rail and trolley bus system is a 600 volt nominal direct current overhead trolley wire system. The light rail system is 159 wire miles in length which utilizes direct suspension OCS with 4/0 grooved trolley wire throughout the system. Prior to 1982, and after the Philadelphia Transportation Co. rail to rubber conversion of 1955-1958 reduced the light rail vehicle count from 1900 to 570, all light rail vehicles remaining were PCC cars equipped with trolley poles and trolley wheels for current collection. Remaining PCC cars that operated until 1991 when PCC operation ended were also equipped with a sliding shoe. The light rail operations of the Philadelphia Suburban Transportation Co. utilized PCC cars with a sliding shoe for many years prior to the SEPTA takeover in 1970. When these PCC cars were phased out and replaced with double ended Kawasaki cars, they were equipped with pantographs for current collection.

In 1991, new light rail vehicles were introduced to the system, being designed and built by the Kawasaki Company as a replacement to older PCC cars which were no longer being manufactured. The SEPTA LRV utilized a trolley pole with sliding shoe for current collection and the existing round 4/0 trolley wire had to be replaced with grooved wire completely for accommodating the trolley shoe operation.

Trolley bus current collectors have changed little since inception in the 1930's in that a sliding shoe contacts the trolley wire for current collection and the trolley wire continues to be 2/0 grooved since initial operation.

The new 4/0 grooved trolley wire incorporated into the light rail OCS proved practical for poles with sliding shoe current collection. The remaining portions of the OCS were not renewed except on an as needed basis and when done so, it was replaced in kind. The existing span wire that supported the trolley wire from poles, buildings and bridges for both light rail vehicles and trackless trolleys continued to be problematic when dewirements occurred. As span wires consisted of steel strand, they were conductive, and broken wires hanging down could be energized at 600 volts if they were in contact with the trolley wire. These hanging down wires made them a hazard to life and property. The Authority could not operate confidently, safely or efficiently with this danger and starting in 2000, after a three year study of alternative solutions, the Authority made the decision to replace the supporting steel span wire network of the OCS with non-conducting span wire.

SYSTEM DESCRIPTION

Existing Overhead Contact System

The existing overhead contact system was established at the turn of the last century in that the current collection system for the streetcars was an overhead contact wire supported by span wires attached to poles. The contact wire was a 4/0 round hard drawn copper trolley wire later changed to a bronze alloy 55 trolley wire when these alloys were developed. The supporting wires from poles were and are still called span wires and are made of steel wire in a 7 strand configuration also known as guy wire.

Poles are either of wood, concrete or steel pipe conforming to SEPTA and ATEA standards for their construction and are directly embedded in the ground with steel poles having a concrete foundation. By the very nature of being inserted into an excavated hole in earth, the bottom of the pole is essentially in direct contact with soil and is therefore solidly grounded even with concrete poured around it. Wood poles have substantially more resistance but electrical leakage occurs when the pole is wet and road salt is spread at its base. The steel span wire, therefore, must be insulated from the energized contact wire and SEPTA uses two levels of insulation referred to as "double insulation". SEPTA OCS conforms to all applicable codes and local statutes such as the National Electric Safety Code [1] and the former American Transit Engineering Association. The double insulation was set up in two locations in the OCS.

The first level of insulation was at the connection of the span wire to the trolley wire through a clamp that is known as a "hanger". This consisted of a malleable iron casting that could be twisted and sprung onto the steel span wire with an insulating cap with stud and an insulating containment cone that allowed the stud to be screwed onto a clamp, called an ear, for trolley wire attachment.

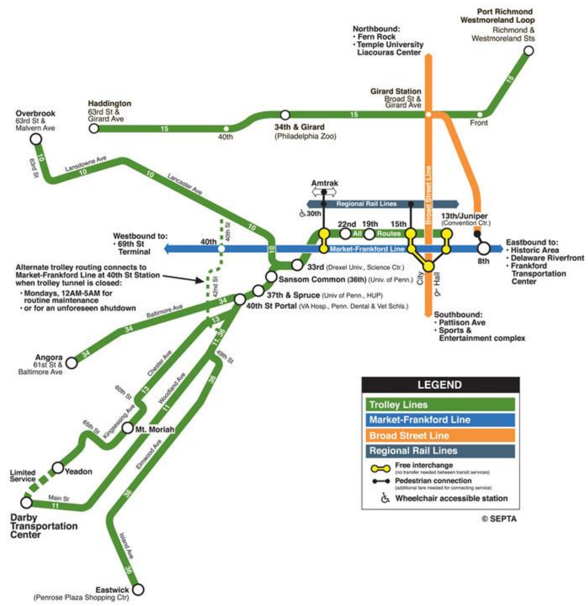

Figure 1. Map of SEPTA Light Rail System

The second level of insulation was directly at the pole where the steel span wire is attached to another insulator, originally a wood, and then later changed to a fiberglass strain insulator sometimes referred to as a "stick insulator". In the event the insulator at the trolley wire failed, the span wire would become energized but the pole insulator kept the span wire from short circuiting to "ground" (Figure 2).

Due to the fact that the OCS is a direct suspension, when dewirements occur, dewired trolley poles can strike against the span wires with forces of such intensity that the span wire are sheared and fall. Coupled with the speed of the streetcar and the spring action of the pole, span wires can sometimes break at the pole insulator as well.

Steel span wires are not shock absorbing and prone to breakage from trolley pole "hits".

Figure 2. Trolley Wire Support with Steel Span Wire

The SEPTA Green Line transports almost 27,595,800 commuters annually along densely populated routes and 5,238,678 passengers annually on the trackless trolley routes. Reliability and safety of the OCS to insure continuity of service is critical. Broken span wires prevent lines from operating trolley and trackless trolley service and buses have to be substituted for transporting passengers. Lack of light rail vehicle operation with substitute bus service severely limited the various line capability to provide efficient reasonable service. The reliability and safety of the OCS is critical to the reliable sustained service that the public demands and to which the OCS of the Authority is expected.

Background of Non-conducting Span Wire

Non-conducting span wires (span rope), also referred to as insulating synthetic rope, were first introduced for OCS suspension in the mid 1980's in Europe. They are constructed with an inner core of synthetic filament yarn fibers covered by a protective sheath of synthetic material. Numerous types of synthetic ropes are available and in use in Europe with an overall EU standard for their construction and use under EU EN 50435. The span rope used by SEPTA has Aramid based synthetic fiber strands which are integrally encapsulated by a tough polyurethane jacket which is colloquially known as "Phillystran®".

Span rope was introduced in North America about the same time it was being used in Europe and transit agencies were cautious to apply it as a complete replacement for steel span wire. Although small sections were put on trials, the major use for span rope was in Delta suspension of the contact wire at span wires and bracket arms. When used as span wire, the non-conducting insulating properties became very apparent and the use of span rope as a trolley wire suspension span increased.

Initially, factors limiting the embrace of span rope wires were creep, breakage due to dewirements and required use of costly special fittings to support and attach it to poles and OCS fittings. This contributed to prevent many agencies from adoption of span rope type wires but due to improvements in construction of the ropes, these restrictions have been reduced or eliminated.

PROPERTIES OF SYNTHETIC ROPE

The nominal breaking load and creep of synthetic ropes are different from steel span wires in that the elastic behavior of steel span wires conforms to Hooke's Law where a plastic deformation occurs after a limiting value. There is no elastic limit for synthetic ropes as they are elastic up to the breaking load and the Hysteresis curve associated with steel span wires is not applicable. Depending upon the application, this can be either be limiting or be an advantage.

Creep in synthetic ropes when compared to steel span wire is greater when put under the same conditions. Steel wire has a higher tensile strength than synthetic ropes of the same diameter but this is not a disadvantage as the applied tensile loads for Kevlar span wire are much lower than the actual breaking strength.

Steel span wire is visibly smaller because a smaller diameter is sufficient for the same load but must have an insulator cut into it with its associated support fittings which increases its visual bulk.

Creep

Creep is the continuing extension of a material under constant load. With synthetic rope, creep varies with the materials of construction but Kevlar ropes have a smaller creep extension than other types of rope such as polyester but still greater than steel span wires which must be considered in application. Tests for creep performed by manufacturers using polyester ropes which have greater creep indicate that the extension of a rope under load for extended periods of time has an initial stretch and then minimal stretch over time. Figure 3 shows a polyester rope under load and the resulting length due to creep.

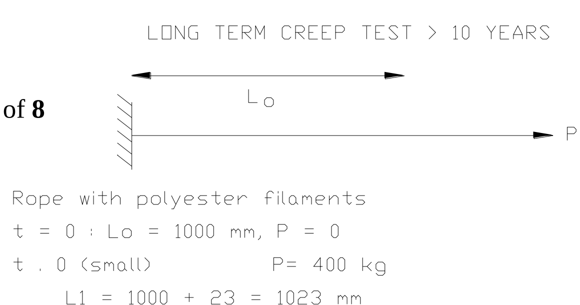

Figure 3. Load Creep for Polyester Synthetic Rope

The long term test results of ropes with polyesters and ropes with Aramid filaments are shown on Figure 4. With loads applied at 40% of breaking load, the polyester filament rope increased in length 2.3% while under exact conditions, the Aramid filament rope increased by only 1.5%.

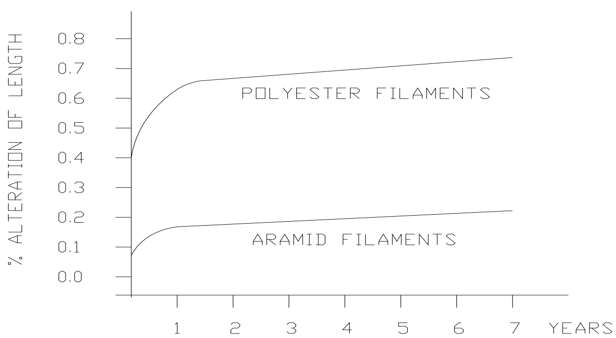

Figure 4. Long Term Test Results of Synthetic Rope

Fatigue and Dynamic Loading

Fatigue and dynamic load of synthetic rope show very good behavior where a high fatigue level has been shown. For ropes cycled below the fatigue limits, no significant deterioration has been observed. Ropes cycled between 10-40% of nominal breaking load and 12 x 10^6 at 13 cycles/sec, showed no significant change of breaking load. Polyester ropes being less stiff than Aramid filament ropes show slightly better behavior.

The synthetic rope (span rope) chosen by SEPTA, known as "Phillystran®", is a Kevlar based filament with an integral, non-separable polyurethane jacketed rope which displays better strength and toughness than the tested ropes discussed previously. The properties of "Kevlar Span Rope" at SEPTA are shown on Table 1.

TABLE 1

KEVLAR* 29 ARAMID YARN PROPERTIES

	U.S. UNITS	METRIC UNITS
Tensile Strength Resin Impregnated Yarn Dry Yarn	 525,000 psi 425,000 psi	 3,620 MPa 2,930 Mpa
Tensile Modulus (Single Filament) Yarn	 12 x 10^6 psi 8.5 x 10^6 psi	 82,700 Mpa 58,600 Mpa
Elongation at Break	3.7%	3.7%
Density	0,05 lbs/in^3	1.44 g/cm^3
Filament Diameter (1.5 dpf)	0.00048 in	0.00122 cm
Specific Tensile Strength **	10 x 10^6 in	25.4 x 10^6 cm
Specific Tensile Modulus**	2.4 x 10^8 in	6.0 x 10^8 cm
Coefficient of Friction Yarn-to-Yarn Yarn-to-Metal	 0.46 0.41	 0.46 0.41
Knot Strength	35% of Tensile Strength	
Maximum Temperature Long-Term use in Air	320° F	160° C
Decomposition Temperature	930° F	160° C
Longitudinal CTE (0-100°) ***	-2.2 ppm/° F	-4 ppm/° C
Transverse CTE (0-100°C) ***	33 x 10^{-6} ppm/°F	59 x 10^{-6} ppm/° C
Specific Heat, R.T.	0.34 BTH/lb	1420 J/Kg° C
Heat of Combustion	15,000 BTU/lb	34.8 x 10^6 J/Kg
* DuPont Registered Trademark		
** Tensile Modulus of Strength dived by Density		
*** Coefficient of Thermal Expansion		

Environmental Influence Resistance

Span rope exhibits resistance to a number of environmental influences giving an advantage over traditional steel span wires from a practical perspective as regards rail transit systems such as SEPTA. These advantages are as follows:

<u>Corrosion Resistance</u>

Synthetic ropes show excellent resistance when compared to normal galvanized steel span wires in that there is no corrosion such as rust. Depending on the type of sheath employed, the corrosive action of salt water, ignoric salts, acids and many organic solvents, synthetic ropes greatly resist these destructive actions.

Resistance to Sunlight

The sheaths applied to ropes of polyethylene and ethylene copolymers of black color are especially formulated for maximum resistance to ultra violet ray degradation. Experiments performed in the state of Florida where the ropes with these sheath compounds were exposed to direct sunlight did not cause any significant degradation or embrittlement [2].

Ice Coating Resistance

Tests carried out in the British Aerospace Corporation climatic chamber demonstrated that the adhesion between ice and the smooth water repellant surface of the synthetic ropes was very poor indicating superiority over steel span wires in the prevention of ice coating.

Trials in Icelandic waters have shown that mast guys stay free of ice by themselves and coupled with the ship's vibrations transmitted to them through the rigging [2].

Effects of Temperature

Synthetic ropes can be used safely over a wide temperature range of -50°C to +80°C (-58°F to 176°F) where the ultimate strength is unaffected [3]. There can be a very slight increase in length at elevated temperatures but the expansion/contraction is much less than steel span wires so that tensions do not change radically. With steel span wires, failures have occurred during cold temperatures by snapping and they sag excessively during elevated temperatures in summer months.

Impact Damage and External Influence

Initial trials and use of the original polyester and Aramid filament ropes with sheaths that were separable from the filaments found that ropes could be damaged or severed from trolley pole dewirements (trolley bus lines) [2]. The span rope used by SEPTA is more resistant to the impacts of wild trolley poles than earlier versions of the ropes although somewhat less resistant to breaking as with steel span wires which is somewhat of a concern. If the outer jacket is cut from a dewired trolley pole the fiber strands become compromised which then becomes a maintenance consideration.

Electrical Properties

The great advantage over steel span wire are the electrical properties of synthetic rope as it is non-conducting, a functioning mechanical structural member and an insulator simultaneously. Electrical tests performed on the Kevlar 29 material indicate that it has very high dielectric strength and is capable of being used at voltages far in excess of 600 volts direct current.

A series of electrical tests were undertaken on Phyllistran® Kevlar PS29J rope at the Frank B. Black Research Center of the Ohio Brass Company in Wadsworth, Ohio in 1974 with excellent results and are shown in Table 2.

TABLE 2		
ELECTRICAL TEST RESULTS		
60 Hz flashover and withstand test	Results Dry	Results Wet
	Average: 239 kV	Average: 92 kV
Positive Impulse and Flashover Test Jacketed Cable	Flashover on various test samples 309 kV-553 kV	
Negative Impulse Flashover Test 1x45 µsec wave	Flashover on various test samples 309 kV-553 kV	
60 Hz Leakage Current Test	Dry with Shield	Wet with Shield
	Volts: 100 kV	Volts: 125
	Leakage Current: 90 µamps	Leakage Current: 1,000-1,500 µamps

The electrical tests confirmed the electrical insulating capability of span rope and that it could be used both as a structural member and an insulator in the OCS.

OCS Construction

Construction of the OCS with steel span wires for a new line where no trolley wire or OCS existed was not problematic for line crews as there were no energized conductors to be cautious of. Care did not have to be exercised to prevent dropping a steel span across the trolley wire on a streetcar or trolley bus and thus steel span wire was of no concern. However, rebuilding of existing lines requires care.

Running new spans across energized streetcar trolley wires required caution but could be undertaken, although judiciously. Crews could lift it up over the trolley wires by keeping it isolated from any "grounds". Care also had to be exercised when attaching to or removing steel span wires from grounded steel poles which were under energized feeder cables with festooned (decaying or missing) insulation. Trolley bus span wire replacement, however, required extreme caution and special consideration when pulling the steel span wires over the twin trolley bus wires which consist of a positive and negative 2/0 grooved alloy 55 trolley wire spaced 24 inches apart. Any contact with the two wires simultaneously by a steel span wire would cause a short circuit with a large electrical arc and explosion resulting.

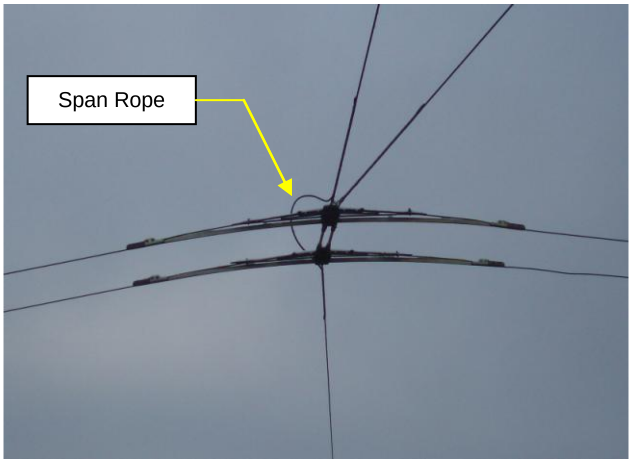

Figure 5. Span Rope Connecting Trolley Bus Wires

Both streetcar and trolley bus overhead required the use of span wire termination devices that were sized to fit the particular size of span wire being used. Older practice methods used varying sizes of span wire dependent upon the specific location requirement. Where tensile loading was high, 3/8 inch span wire was used and where loading was light to medium, 5/6 inch was used with both types being 7 strand galvanized guy wire. Older terminations were made by wrapping each individual strand around the entire wire at the OCS fitting. Newer fittings were consistent with utility style termination devices such as Strandvises or Preformed End Fittings.

Where the steel span wire was looped and tied off into a termination at the OCS fitting, there was a tendency for the ends of the strands to rust as they had been cut exposing bare metal to the environment. The spans also corroded at the interface of the insulated hanger as they were wrapped around them in an offset fashion through the hanger's arm ears as moisture was trapped. On occasion, the corrosion coupled with a constant flexing from the dynamic uplift of the streetcar trolley pole would cause the steel span wire strands to fatigue and break causing the wire to fall into the street.

Using span rope, one size could be used for all applications as it possessed high strength and light weight. Two types of termination fittings could be used making installation convenient and simple. The span rope did not have to be cut at trolley bus special work but could be left as a single piece across the wires and only attached at the poles (Figure 5).

Conversion Installation

Method of Work

With the decision to convert the existing span wire to non-conducting synthetic ropes a systematic plan was developed and initiated to convert over 15,000 spans that have been in service since the 1950's. As part of the annual span wire replacement program, 500 spans are replaced annually with line crews being able to change an average of 5 steel spans a day to span rope. Costs associated for crews to install various types of spans are shown on Table 3A, 3B 4A & 4B. Table 5 shows the comparative costs between steel span wires and span rope.

Operational Improvements with Span Rope

The operation of the areas of the lines equipped with the non-conducting span wires showed no adverse affects to current collection of vehicles equipped with trolley poles or pantographs. A slight improvement to elasticity of the OCS at the supporting spans was noticed as uplift increased due to the light weight of the span rope. Although not particularly significant in uplift, any improvement contributes to reduction of contact wire wear at the wire/ear interface.

Span rope has provided an extremely significant safety improvement with operations where any span ropes that fall down and simultaneously contact the energized trolley wire and the street will not cause electric shock to persons or animals. This in itself is one of the major advantages to this type of trolley wire support and has eliminated fallen span wire shocks and subsequent litigation.

COST SAVINGS

Prior Costs and Saved Costs from Conversion

The overall material costs for synthetic ropes were examined for the conversion and found to be more economical for both tangent and curve construction than that of steel span wires when labor costs were factored in. Not having to install 6 inline insulators improved production from 5 spans a shift to 10 spans per shift

TABLE 3A			
MATERIAL COSTS-STEEL SPAN WIRE			
Material	**Avg. Unit Cost**	**Quantity**	**Cost**
Insulators	$40.00	6	$240
Trolley wire hanger & clips	$96.00	2	$192.00
Pole bands	$58.00	2	$116.00
Total Material Cost per span			**860.00**

TABLE 3B			
LINE CREW COSTS-STEEL SPAN WIRE			
Standard Line Crew		**Rate per Hour**	**Total Daily Rate**
1	Foreperson	$52.00	$416.00
1	First Class OH Maintainer	$49.50	$396.00
4	2nd Class OH Maintainer	$47.40	$1,516.80
		Total Daily Cost	**$2,328.80**
		Labor Per Steel Span	**$465.76**

TABLE 4A			
LINECREW COSTS-SPAN ROPE			
Standard Line Crew		**Rate per Hour**	**Total Daily Rate**
1	Foreperson	$52.00	$416.00
1	1st Class OH Maintainer	$49.50	$396.00
4	2nd Class OH Maintainer	$47.40	$1516.80
		Total Daily Cost	**$2328.80**
		Labor Per Non-Con Span	**$232.88**

TABLE 4B			
MATERIAL COSTS-SPAN ROPE			
Material	**Avg. Unit Cost**	**Quantity**	**Cost**
Fiber	$2.00	100	$200
End kits	$19.00	2	$38.00
Trolley wire hanger & clips	$96.00	2	$192.00
Pole bands	$58.00	2	$116.00
Total Material Cost			**$546.00**

TABLE 5		
COMPARITIVE COSTS		
	Steel	**Span Rope**
Labor	$465.76	$232.88
Material	$860.00	$546.00
Total	$1325.76	$778.88
	Delta per span	**$546.80**
	Saving per Year	**$273,400**

AESTHETIC CONCERNS

Visual Aesthetic Improvements

Along with a significant savings in installation costs and safety considerations, an improvement in the aesthetic appearance of the OCS became apparent with the standardization of span wire diameters. A reduced mass from insulators allows the OCS to have a tendency to blend into the background whether it be the sky or the cityscape. OCS has long been a concern for local communities where there is a feeling that all overhead wires cause unsightly visual pollution and with this considered, all current and future Authority designs utilize aesthetics in the choice of the OCS and the way it is supported.

Consideration is given to the use of joint use poles which will support OCS, street lighting and or traffic control lighting to reduce the number of poles in any one given area. This not only creates a more visually appealing streetscape but is economically efficient for all municipal participants.

Many designers seem to have ignored the importance of simple, non-obtrusive overhead where the visual appearance of the OCS should always be of concern [2]. All new synthetic span systems significantly reduce visual pollution and are an enhancement to the overall overhead aesthetics of the SEPTA system.

CONCLUSION

Replacing steel span wires with non-conducting synthetic ropes has allowed SEPTA to improve operational performance, reduce maintenance costs, insure line worker and public safety and increase overhead contact system aesthetics.

The existing OCS suspension system with steel span wires although functionally acceptable, was deemed undesirable and potentially dangerous due to fallen span wires becoming energized so Authority personnel installed replacement OCS support using Kevlar synthetic ropes. This provided line crews the ability and confidence to install spans quickly and efficiently without fear of short circuiting the trolley wire while building a standard OCS as they had been trained to do. A significant reduction in the wear patterns of the contact wire was realized that now allow longevity in years of life before replacement is required.

Given the fact that non-conducting span wire is slightly more expensive initially than steel span wire, the operational, maintenance and economical advantages of an OCS with this type of suspension far outweighs that of steel and is now the choice of construction for use on the Southeastern Pennsylvania Transportation Authority.

ACKNOWLEDGMENTS

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END NOTES

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2. "Synthetic Ropes used for overhead contact line construction especially ropes on the basis of polyester fibers and Aramid (Kevlar) fibers", lecture given by Mr. Daniel Steiner, Dipl. Eng. ETH on the occasion of the Trolleybus-Conference, on January 18th, 1989, Geneva, Switzerland.
3. John S. Kulpa and Arthur D. Schwartz, "Reducing the Visual Impact of Overhead Contact Systems", Transit Cooperative Research Program Report No. 7, 1995.
4. Technical Bulletin 163-6/97, Phillystran, Inc., 1997

LIST OF FIGURES

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