

# NEXT GENERATION HIGH PERFORMANCE ADSS CABLE DESIGNS WITH HIGH MODULUS REINFORCEMENT MATERIALS

**Swati Neogi, Jeff Auton, Brian G. Risch\*\*, and Dean Rattazzi**  
Alcatel Fiber Optic Cable R&D, Claremont, NC

\*\*To whom correspondence should be addressed.

## ABSTRACT

New ADSS designs are presented that contain PBO fibers with a modulus 220% that of para-aramid. The use of higher modulus PBO materials allows substantial improvements over traditional para-aramid reinforcement in terms of cable MRCL, maximum fiber count, maximum span length, and cable manufacturing lengths. A study of dynamic fatigue lifetime for PBO fiber is also presented that shows that high performance cable designs containing PBO fibers can withstand over 1 000 000 loading and unloading cycles. Although the cost of the PBO material is high relative to aramid, this study shows that this new material is well suited for specialty high load ADSS applications.

**KEYWORDS:** ADSS; Aramid; Fatigue; Lifetime; PBO; Reinforcement; Reliability

## INTRODUCTION

All Dielectric Self-Supporting (ADSS) fiber optic cable offers a rapid and economical solution for utility and telecommunication companies to deploy optical fiber cables along existing electric and telephone utility pole rights of way assets. ADSS cables offer an alternative solution over other aerial application cables such as lashed or Figure-8 cables. All dielectric solutions are preferred and sometimes mandatory for installation in or near electric power lines on utility structures where cables containing metallic elements are not advised.

High modulus reinforcement elements are used in aerial cable reinforcement to minimize cable diameter and weight for a given MRCL and fiber count. Traditionally para-aramid fiber has been used due to its excellent combination of high modulus, low density, and high electrical resistivity. Poly(p-phenylene-2,6 benzobisoxazole) (PBO) fiber offers a superior modulus to weight ratio even when compared to para-aramid. Unlike steel and carbon fiber, which also have a high modulus, PBO also has high electrical resistivity making it an interesting candidate material for ADSS cables.

A comparison of properties of cable reinforcing materials is shown in Tables 1,2, &3 .

**Table 1a:** Comparison of Physical Properties of Various Cable Reinforcing Materials.

Material:	Young's Modulus	Density	Specific Modulus [Gpa(cc/g)]
PBO Yarn	280 GPa	1.56 g/cc	180
Carbon Fiber	255 GPa	1.77g/cc	144
p-Aramid	95-120 GPa	1.44 g/cc	66 - 83
E-Glass	73GPa	2.60 g/cc	28
Steel	200 GPa	7.8 g/cc	25
GRP	50 GPa	2.40 g/cc	21
Polyester	18 GPa	1.38 g/cc	13

**Table 1b:** Comparison of Strength of Cable Reinforcing Materials.

Material:	Strength (GPa)	Elongation(%)
PBO Yarn	5.6	2%
Carbon Fiber	3.8	1.7%
p-Aramid	3.0	2.5%
E-Glass	3.5	4.8%
GRP	1.5	3%
Steel	4.0	2%

**Table 2:** Comparison of Electrical Resistivity of Various Cable Reinforcing Materials.<sup>1</sup>

Material:	Resistivity (Ω-cm)
PBO Yarn	7 E 6
Carbon Fiber	1.5 E -3
p-Aramid	7 E 6
E-Glass	5 E 9
Steel	10 E -6

**Table 3:** Comparison of Coefficient of Thermal Expansion of Cable Reinforcing Materials.<sup>1</sup>

Material:	CTE @ R.T. (per °C)
PBO Yarn	-6.0 E -6
Carbon Fiber	0.6 E -6
p-Aramid	-4.2 E -6
E-Glass	2.8 E -6
GRP	6 E -6
Steel	6.7 E -6

Besides properties such as modulus, tensile strength, density, and coefficient of thermal expansion, the resistance to fatigue under continuous and varying loading conditions is critical for ADSS cable reinforcement materials. If ADSS cable reinforcement materials do not possess adequate fatigue resistance, the

cables can fail under relatively low loads after extended service life.

Aramid has been used in load bearing applications such as ADSS cables, composites, ropes, and drive belts for years, and a substantial body of research has been compiled on the long term reliability of various Aramid fibers. However, less data is available for PBO yarn. For continuous load applications various approaches have been used to predict the lifetime of reinforcing fibers depending on the application. For static loading a two parameter Weibull distribution has been used to model both strength and creep rupture of individual aramid fibers.<sup>2,3,4</sup> The Weibull approach to modeling fiber strength is already commonly used to model optical fiber strength and fatigue lifetime.

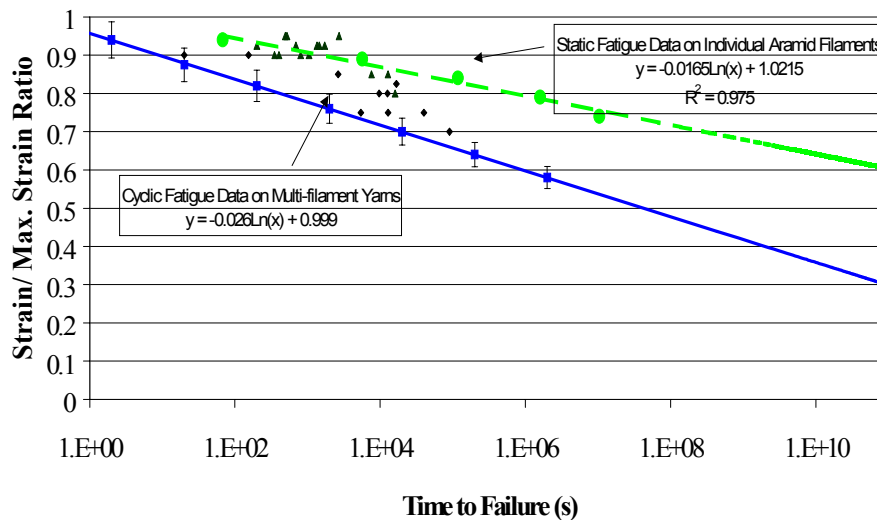
In ADSS cable applications loading conditions are seldom constant due to ice and wind load variability. Variable loading components from wind and ice are superimposed on a static component contribution from cable weight. For cyclic fatigue alternative lifetime models have been developed. A logarithmic relationship has been established between median fatigue lifetime and applied stress amplitude in cyclic fatigue testing.<sup>5</sup> These cyclic fatigue tests have also produced substantially lower filament lifetimes at equivalent stress levels when compared to static fatigue tests on single aramid filaments. For example, median Weibull fatigue lifetime for single aramid filaments at 70% of break stress ( $\sigma_B$ ) under constant loading is 4 orders of magnitude longer than that observed for median cyclic loading lifetime at 5hz. Figure 1 is a comparison of literature data from

references 3 and 4 that also includes data collected in the current study in black.

The variation between static fatigue lifetimes of individual aramid filaments and cyclic fatigue lifetimes of aramid yarns is likely due to a combination of: uneven load distribution between individual filaments in yarns, redistribution of load between yarn filaments during testing, and abrasion damage that can occur when individual filaments rub together during cyclic fatigue testing. Due to the fact that ADSS cables experience variability in loading due to vibration as well as changes in wind and ice loading, a cyclic fatigue evaluation has been selected to establish fatigue lifetimes in this study. Additionally, the effects of varying static and dynamic components of load on fatigue lifetime are evaluated which allows an insight on how variations of cable loading conditions can alter fatigue lifetime. The use of actual yarns vs. individual filaments in the testing allows a proper consideration of load distribution and abrasion during fatigue testing. Evaluation of lifetime based on yarn cyclic fatigue testing prevents the risk of underestimating fatigue life that could be possible in static fatigue testing of single filaments.

Figure 1 illustrates that most of the experimental data from this study falls between the two curves obtained in earlier studies. The variation between earlier results and those obtained in the current study can be attributed to variation in loading conditions. The logarithmic slope for the two data sets, however, did not vary substantially from the values obtained in earlier studies.

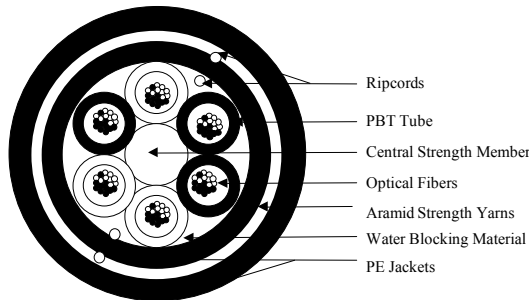
Figure 1: Comparison of Fatigue Life Testing Methods for Aramid



## EXPERIMENTAL

ADSS cables were designed with Polybutylene Teraphthalate (PBT) tubes containing optical fibers stranded around a central strength member. Superabsorbent waterblocking materials were used to make the interstices between the tubes watertight.<sup>6</sup> The inner core was surrounded by an inner sheath made of Medium Density Polyethylene (MDPE). Between the inner sheath and outer sheath strength yarns were applied. The material of the outer sheath can be either HDPE or a track resistant filled thermoplastic for applications where enhanced resistance to electrical activity is desired.<sup>6, 7,8</sup> A diagram of the cable construction is shown in Figure 2.

**Figure 2.** Schematic Representation of the Cross Section of Typical ADSS Cable.



### Yarn Mechanical Testing:

#### Cyclic Fatigue Testing:

Mechanical testing was performed using an Instron 5567 tensile tester. A 400-pound load cell was used with Instron's "5kN" pneumatic cord and yarn clamp.

The first segment of the test was performed in tensile extension control at a rate of 50mm/min. The second segment, or cyclic portion of the test, was performed in the load control mode with the upper limit being set for a percentage of the load at rupture and the lower limit set to half the value of the upper limit. Since the 5567 model is an electro-mechanical device the distance between the two limits in the cyclic segment was kept large enough so that there was no danger of burning out the motor or having a large load overshoot. Typical cycle time was about 3.4 seconds, or 17.64 cycles per minute, which corresponds to a frequency of 0.29Hz.

Limits for the cyclic portion of the test were based on the ultimate tensile strength of the various materials. The ratio of maximum load (or stress) to the break load (or stress) of the yarn can be defined by  $R_{Max} = \sigma_{Max} / \sigma_B$ . For a majority of the tests, the lower load was set to a value that corresponded to one half of the maximum stress value in the loading pattern, and the load was varied between the

maximum and minimum values through a linear sawtooth wave pattern. The tensile loading pattern used resulted in a sawtooth load function being superimposed on a static load. This method of setting limits was repeated for various  $R_{Max}$  load levels with  $R_{stress}$  being kept constant at 50%.

#### Tensile Testing and LASE Data:

LASE (Load At Specific Elongation) data as well as tensile test data are obtained from the same test method and typically from the same test. Mechanical testing was performed using an Instron 5567 tensile tester. For this test a 6700-pound load cell was used with Instron's "5kN" pneumatic cord and yarn clamp. The gauge length was set for 635mm.

The test was performed in tensile extension control mode at a rate of 320mm/min. A pretension load of 1-3 lbf was applied by hand to the sample to reduce the amount of slack and toe observed during the test. LASE was calculated using the gauge length above over the range of 0.1 - 1.0 % elongation in 0.1% increments such that 0.125 inches of elongation is equal to 1% LASE.

## RESULTS AND DISCUSSION

### Effect of Load Variability on Fatigue Lifetime:

In the fatigue test method a variable load was superimposed upon a static load. Since the mechanisms between cyclic and static fatigue may vary the effect of varying the dynamic and static contribution was investigated. Initial testing of all yarns was performed to determine maximum tensile stress,  $\sigma_B$ . In the lifetime prediction model the ratio of maximum applied stress to break stress ( $R_{Max} = \sigma_{Max} / \sigma_B$ ) is the dependent variable. Additionally, the loading applied during testing consists of a static load contribution and a dynamic load contribution that is superimposed on the static load contribution in the form of a wave pattern. In this case the wave pattern was a linear sawtooth pattern. The load, therefore, varies and a minimum and maximum load and stress exists within the load profile.

In addition to the maximum stress applied during testing, the ratio of the minimum to maximum load also has an effect on cycles and time to break. As illustrated in the earlier review of literature, completely static loads produce the longest time to failure. As the dynamic contribution of the load increases (i.e.  $R_{stress} = \sigma_{min} / \sigma_{Max}$  increases), time to failure decreases dramatically even though average load is reduced by a factor of  $[(R_{stress} + 1) / 2]$ . This factor is always less than unity in cyclic load fatigue tests, and in the case where  $R_{stress} = 1$ , we have a simple static fatigue test that can be performed according to the same experimental procedure.

Some examples of the effect of varying  $R_{stress}$  while keeping  $R_{Max}$  at 93% are illustrated in Table 4.

**Table 4:** Effect of varying  $R_{stress}$  on cycles to failure in aramid cyclic fatigue testing with  $R_{Max}=0.93$ .

$R_{stress}$	Cycles to Break
0.93	2600
0.50	516
0.10	263

**Fatigue Testing:**

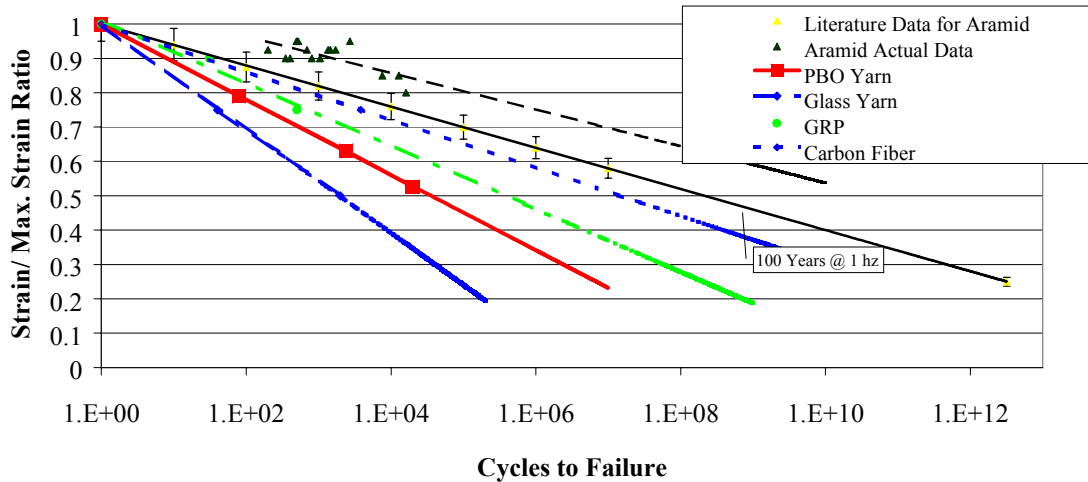
Cyclic fatigue test data was obtained on a p-aramid, PBO, glass yarn, GRP rod, and carbon fiber; the results are

poor fatigue performance for continuous load applications. Combined with the obvious weight disadvantage for glass reinforced aerial cables, it is apparent why materials such as aramid or PBO are preferred for ADSS.

**Table 5: Slope of Maximum Stress Ratio to Log of Cycle Time Curve for Cyclic Fatigue Testing.**

Material:	Log Slope
p-Aramid	-.026
Carbon Fiber	-.030
GRP	-.040
PBO Yarn	-.045
E-Glass	-.066

**Figure 3: Fatigue Life of Various Cable Reinforcing Materials**



shown in Figure 3. A great deal of variability exists in the fatigue lifetime of these materials. In order to properly interpret the data for an ADSS cable design, a relation to actual loading conditions is needed since both break stress and elongation to break for the materials also varies and the  $R_{Max}$  value is normalized according to break stress of each material. An example of relating fatigue data to an actual ADSS application is provided in the cable performance section of this paper.

The fatigue lifetime of the materials can be ranked according to the slope of the plot of stress ratio vs. Log of cycles to failure. Slopes that are smaller in magnitude indicate better fatigue life and less deterioration of properties with time. Table 5 is a comparison of the slopes of the fatigue lifetime curves shown in Figure 3. The fatigue lifetimes of both para-aramid and carbon fiber are superior to Zylon, but the performance of Zylon is very close to that of GRP. GRP has been used in ADSS cables as a central element with a long known performance history in cable reinforcement. The types of glass cable reinforcement yarns tested in this study show

Figure 4 illustrates that, as with aramid fibers, the fatigue life of PBO fibers is reduced when going from static to cyclic loading. As with the cyclic fatigue test results, static load fatigue test results are slightly poorer for PBO relative to aramid yarns. As with the cyclic fatigue data, a logarithmic slope can be obtained to rank the fatigue lifetime of the materials under static loading conditions. The logarithmic slopes for static load fatigue tests are shown in table 6.

**Table 6: Slope of Maximum Stress Ratio to Log of Cycle Time Curve for Static Fatigue Testing.**

Material:	Log Slope
p-Aramid	-.0165
PBO Yarn	-.0227

**Table 7: Comparison of Log Slopes of Static and Cyclic Fatigue Curves for Aramid and PBO Yarns.**

Material:	Log Slope		
	Static	Cyclic	Difference
p-Aramid	-0.165	-0.026	58%
PBO Yarn	-0.227	-0.045	98%

Table 7 illustrates the relative effects of changing load conditions on fatigue life of PBO and aramid yarns. When load conditions were changed from static to cyclic, aramid yarns showed a 58% decrease in the log slope of the fatigue curve whereas PBO yarn showed a 98% decrease. This data indicates that PBO yarn fatigue life is slightly more sensitive to loading conditions than aramid yarns. Based on this data, it is important to properly evaluate cable applications for PBO yarn and compare to fatigue data in order to ensure proper in-service reliability. Evaluation of an actual service application is included in the following section of this paper.

**Cable Performance:**

Four 144f ADSS Cables were designed to compare performance in ADSS cables of PBO and aramid. Two cables were designed for NESC Medium loading at a span length of approximately 120m (400ft.), and two cables were designed for a cable span of 610m (2000ft.) with 51mm of ice loading and a wind speed of 17.6 m/s. Data is presented for a 2% cable sag installation.

Almost no measurable benefit is seen with the replacement of Aramid with PBO for the lower tensile rated cables although the number of yarn ends and volume of yarn was reduced by approximately 50% in the cable. On the other hand, a dramatic improvement is seen in the data for the long span ADSS cable. Due to the higher modulus of PBO, less PBO is needed to reach an equivalent cable load

rating. Additionally, due to a reduction in cable weight per unit length, an iterative effect on cable strength and weight is seen due to the slightly lower cable tensile loading required for the PBO cable.

**Table 6: Comparison of PBO and p-Aramid Reinforced Cables.**

**120m span, NESC Medium loading.**

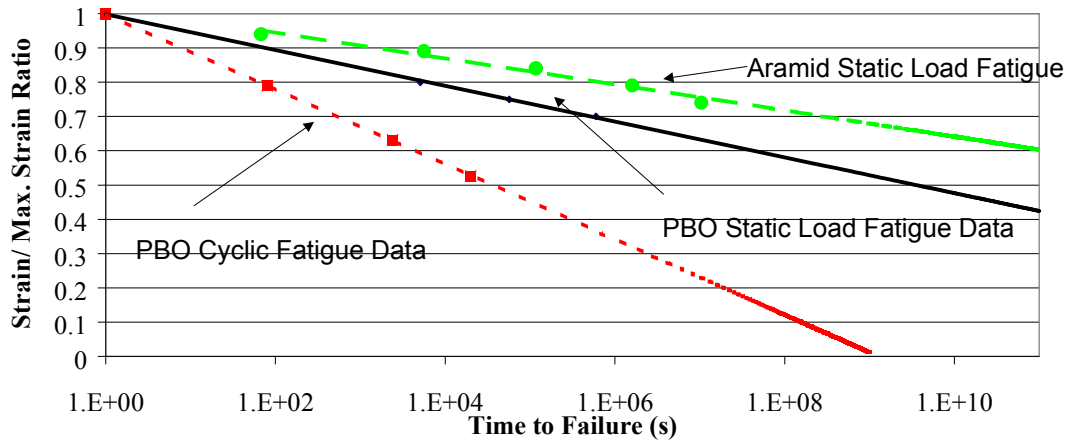
	Aramid	PBO	Improvement
Cable OD	18.9mm	18.4mm	2.5%
Cable Weight	0.331KG/M	0.3418KG/M	3.8%
Cable Modulus	15 KN/%	15 KN/%	-

**610m Span w. 51mm Ice Loading.**

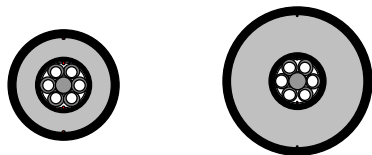
	Aramid	PBO	Improvement
Cable OD	33.8mm	24.5mm	27%
Cable Weight	0.755KG/M	0.424KG/M	43%
Cable Modulus	324 KN/%	277 KN/%	-15%
Installation Sag	2%	2%	-
Installation Tension	28 200 N	15 900 N	44%
Max. Loaded Tension	210 000 N	180 000 N	14%
Max. Elongation	0.65%	0.65%	-

Table 6 illustrates the benefit of using high modulus PBO fibers on extremely long span ADSS cables and Figure 5 shows a graphical comparison of cable cross section. A significant reduction is seen on cable OD and cable weight. The reduction in cable weight also leads to a significant reduction in installation and maximum cable tension. Reduced cable weights and tensions are desired to prevent excessive loading on suspension structures and hardware which are considerable concerns for such a long span cable design.

**Figure 4: Comparison of Static Load Fatigue Life for Aramid and PBO Fibers**



**Figure 5:** Comparison of PBO and p-Aramid Reinforced Long-span, Heavy Ice Load Cables with Identical Load Ratings and 2% Sag.



<b>PBO Cable</b>	<b>Aramid Cable</b>
<b>OD = 24.458 mm</b>	<b>OD = 33.834 mm</b>
<b>Weight =423.79Kg/km</b>	<b>Weight =755.34Kg/km</b>

With the above design, the installation tension results in only about 0.06% cable elongation, or an  $R_{Max}$  value of 0.03. At maximum rated load, the cable elongation would be 0.65%, with an  $R_{Max}$  value of 0.325. Static fatigue testing on PBO fiber indicates that the cable would be able to withstand many thousands of years of static loading at the maximum rated cable load. Additionally, dynamic fatigue testing indicates that the cable reinforcing material could withstand approximately 1 000 000 loading and unloading cycles to this load level. Since the conditions that would produce the severe ice loads required to achieve the maximum rated load would occur seasonally, many years of cable life could be expected for the proposed high modulus PBO reinforced long span cable design. Due to variability between fatigue performance in PBO and Aramid cables, it is recommended to do a fatigue loading analysis to correspond to loading conditions for each new cable design. Different loading conditions may have variable contributions from static and dynamic components and therefore give less favorable lifetime estimations.

## CONCLUSIONS

Materials test data, cable design data, and reliability data have been provided for use of high modulus PBO fiber in ADSS applications. Because PBO has a modulus substantially higher than Aramid, cable weights and diameters can be substantially reduced for long-span ADSS cables through the use of high modulus PBO fibers. For a 610M (2000ft.) high ice load ADSS design, the reduction in cable weight was 43% and the reduction in cable diameter was 27%. Additionally the reduction in installation tension and maximum service tension was reduced by up to 44%. The reduction in cable tension has the added benefit of reducing loads on suspension hardware and structures.

Reliability testing was performed on PBO yarns and compared to aramid, carbon fiber, glass reinforced

composite rod (GRP), and glass yarns. Fatigue resistance of PBO yarns was inferior to that of aramid but comparable to GRP. Due to the fact that PBO and aramid do not have identical fatigue resistance, projected cable loading conditions and cable design specifications should be checked against PBO fatigue data for specific applications. High modulus PBO yarns can withstand approximately 1 000 000 loading and unloading cycles to the maximum rated cable elongation for the long span design presented in this study. When measured fatigue performance of PBO yarns is compared to actual loading conditions for the long span designs presented, many years of reliable service life are predicted.

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## AUTHORS



**Dean Rattazzi**  
*Alcatel*  
*Fiber Optic Cable R&D*  
*2512 Penny Rd.*  
*P.O. Box 39*  
*Claremont, NC 28610*

Dean Rattazzi is a Design Engineer at the Alcatel Fiber Optic Cable R&D Center in Claremont, North Carolina. He holds a BA degree in Physics, and a BS degree in Mechanical Engineering from Binghamton University, and an MS degree in Engineering Mechanics from Virginia Tech. His area of research includes the application of finite element modeling to the design and development of fiber optic cables.



**Swati NEOGI**  
*Alcatel*  
*Fiber Optic Cable R&D*  
*2512 Penny Rd.*  
*P.O. Box 39*  
*Claremont, NC 28610*

Swati Neogi is a Senior Material Scientist and Project Manager at Alcatel's Fiber Optic Cable R&D Center. She received her Ph.D in Chemical Engineering from Ohio University. Before joining Alcatel in 1996, she worked in commissioning a PET plant.



**Jeff AUTON**  
*Alcatel*  
*Fiber Optic Cable R&D*  
*2512 Penny Rd.*  
*P.O. Box 39*  
*Claremont, NC 28610*

Jeff Auton received his B.S in Biology from Lenoir-Rhyne college in 1984. He worked as a QA Chemist in other industries prior to joining Alcatel in 1989. He has been with Alcatel for 12 years in materials development. Currently Jeff is working at Alcatel's Fiber Optic Cable R&D Center as the Materials Testing Coordinator.



**Brian G. RISCH**  
*Alcatel*  
*Fiber Optic Cable R&D*  
*2512 Penny Rd.*  
*P.O. Box 39*  
*Claremont, NC 28610*

Brian G. Risch is the Materials Technology Manager at Alcatel Fiber Optic Cable R&D Center. He holds a B.A. degree in physics from Carleton College and a Ph.D. in Materials Science and Engineering from Virginia Polytechnic Institute and State University. His Ph.D. research was in the area of polymer crystallization and structure-property relationships in polymers. Directly after he finished his Ph.D. he worked for ORD laboratories in the area of optical polymers developing new polyurethane and polythiourethanes for high performance ophthalmic lens applications. Since 1996 Brian has worked for Alcatel's Optical Fiber Cable R&D center specializing in cable materials.