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CHARACTERIZATION OF FIBER OPTIC CABLES UNDER LARGE TENSILE LOADS

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Abstract

Fiber optic cables designed for the Nevada Test Site (NTS) have to withstand an unusually harsh environment. Cables have been manufactured under a 6 year old DOE specification that has been slightly modified as the cable requirements are better understood.

In order to better understand the cable properties a unique capability has been established at the NTS. Instrumentation has been developed to characterize the transmission properties of 1 km of fiber optic cable placed under a controlled tensile load up to 1500 lbs. The properties measured are cable tension, cable elongation, induced attenuation, attenuation vs. location, fiber strain, bandwidth, and ambient temperature. Performing these measurements on cables from the two qualified NTS fiber optic cable manufacturers, Siecor and Andrew Corp., led to a new set of specifications.

The relevant new and old specifications will be reported along with the characterization techniques and results on cables manufactured under the old specification.

Introduction

Tests were conducted in February and March of 1983 at the Nevada Test Site on three fiber optic cables. The cables were fabricated to DOE specifications by two manufacturers: Andrew Corp. and Siecor, Inc. The three cables tested were designated Andrew FO-1, Andrew FO-2 and Siecor FO-2. The Andrew FO-1 was constructed according to an early specification. The other two cables were fabricated according to revised specifications.

The purpose of the tests was to determine cable and fiber performance under tension. The parameters measured were:

- a) cable elongation;
- b) fiber strain;
- c) relative attenuation;
- d) pulse time delay; and
- e) bandwidth.

The results of these tests lead to a more stringent revision of the DOE specifications.

General cable description

All cables were constructed with a non-metallic central strength member surrounded by eight buffered fibers. The Andrew FO-1 cable had very small loose tube buffered fibers. The Andrew FO-2 had a relatively small diameter loose tube buffer and the Siecor FO-2 had a relatively large loose tube buffer. The fibers were wound in a helix on the Andrew cables and a half helix of alternating directions in the Siecor cable. The fibers were covered with a black jacket which in turn was covered with a relatively thick orange coat of polyethylene. All cables were continuously gas-blocked by inserting a viscous gel in all the void spaces in the cable, including the loose tube buffers.

The main difference in the specifications for the cables was the tension requirements. The Andrew's FO-1 was constructed to withstand 200 lbs. tension. The specification for the Andrew's FO-2 and Siecor FO-2 changed to 1500 lbs. tension. Siecor did not revise their design between specifications.

Experimental Arrangement

A 0.5 km strip of the desert floor was cleared of brush. At one end of the strip a recording station was located as shown in Fig. 1. Outside the recording station two 6 ft. diameter cable spools were anchored to the ground. At the other end of the 0.5 km strip an electric winch was anchored to the ground. Tracks were laid for a 1-m diameter sheave to travel on. The sheave was attached to the winch through a load cell to measure the cable tension. A tape measure was laid out to measure the elongation of the cable.

Fig. 1. Schematic of the experimental layout for the fiber optical pull tests.

The fiber optic cable was laid out so both ends were in the recording station. Outside the station each end was wrapped 5 to 6 times around the 6 ft. cable spools with rubber between them and the spools, as shown in Fig. 2. This distributes the load evenly over a long length of cable. The center of the cable went around the sheave, as shown in Fig. 3.

Fig. 2. The fiber optic cable is wrapped around the cable drums in the foreground and the sheave is shown in the background.

Fig. 3. The 1-m sheave is shown on its tracks.

Fig. 4. The schematic shows the distribution of fibers among the various optical measurements.

Each fiber in the cable was dedicated to measuring one of the several parameters of interest. Figure 4 is a general schematic of the measurement made with each fiber.

Fiber strain was measured by using a phase monitoring technique^{1,2,3}. The laser was driven with a 500 MHz oscillator from a network analyzer.

Attenuation as a function of distance was monitored continuously by an OTDR. No attempt was made to restrict launch N.A. since the purpose of this measurement was to verify that load was evenly distributed along the cable.

The bandwidth and pulse time delay measurements were made on the same fibers. It is based on using a Hamamatsu picosecond light source which is spectrally limited to 0.9 nm FWHM at 820 nm by a Spectral Equalizer⁴ that fills the N.A. of the test fiber. The output pulse was monitored by a Varian micro-channel plate photomultiplier tube (VPM 225, FWHM = 185 ps) coupled to a Tektronix DPO. Pulse time delay was measured according to relative positions on the DPO.

Relative attenuation measurements were made on a number of fibers. The light source was a d.c. LED coupled into a fused biconical tapered star coupler. The star was coupled to the fibers under test and the output signals were detected by photovoltaic detectors. The signals were then multiplexed into a digital electrometer which was interrogated by a PDP-11/34 mini-computer. Each fiber was scanned at 30 second intervals. One output of the star coupler went directly to a PIN. This channel was used as the LED reference.

One fiber channel used a d.c. LED light source coupled through the fiber to an EG&G-550 radiometer which drove a strip-chart recorder to give a continuous transmission vs. time history.

Procedure

The first procedure consisted of tensioning a 0.9 to 1.0 Km length of cable in steps until a fiber failed, or 900 lbs. was reached. Initially the steps were 0.6 m in length, but they were reduced to 0.2 m to lessen the effects of cable load relaxation. Time interval between steps generally varied between 1 and 5 min., depending on load relaxation. This procedure was designated the "slow pull".

The second procedure, designated the "fast pull", consisted of tensioning the fiber as fast as possible to 1500 lbs., holding for one minute, then decreasing the tension to 250 lbs. as rapidly as possible. At this point the procedures varied depending on the transmission characteristics of the cable.

The Andrew FO-2 cable was held at 250 lbs. for about 1 hour then dropped to 100 lbs. It was left with 100 lbs. tension on it over night, about 17 hours, then dropped to zero lbs. for about 0.5 hour at which time measurements were discontinued.

For the Siecor FO-2 cable the tension was again held at 250 lbs. for about 1 hour then dropped to 100 lbs. It was held at 100 lbs. for about 20 minutes, then dropped to zero lbs. It was monitored for a few minutes and then measurements were discontinued.

Performance details

Fiber elongation versus cable elongation

It is desirable that tensile loads placed on the cable are supported by the cable strength member without transferring stress to the fibers. This is typically accomplished by using a loose buffer tube and incorporating excess fiber in the tube. As the cable is stressed the whole cable structure elongates with the strength member controlling the rate by virtue of the product of its cross sectional area and modulus of elasticity. The fiber is free to move within the buffer tube, and does not experience stress until the buffer tube elongation has surpassed the excess fiber length.

However, the requirement for DOE downhole cables to be gas blocked creates a somewhat different situation. The space between the fiber and buffer tube is filled with a viscous gel to prevent gas flow. This material checks the free movement of the fiber. The result is a dependency of the fiber movement on the speed and amount of cable elongation or contraction, and also on temperature. These effects were very noticeable on the Andrew cables, and could be seen in some of the Siecor cable tests. It should be noted that there has been no attempt to correct the data for temperature effects. Figure 5 illustrates the same elongation characteristics for both Andrews cables and greater elongation for the Siecor cable.

Fig. 5. Elongation of the 3 cables during the slow pull test.

Andrew FO-1. Elongation steps of 0.6 m in a 905 m length of cable caused a tight buffer tube construction behavior. Fiber strain was immediately seen as the cable was pulled. The temperature was 70°F and the elongation rate was 3.75 m/min.

At a total cable elongation of about 1.2 m and a corresponding load of 150 lbs., the fiber strain would decrease to zero if 7 min or more elapsed. Again, the temperature was 70°F. For this particular cable and fiber being monitored, this was evidently the elongation at which the fiber excess length had been reduced to zero.

Fig. 6. Fiber elongation as a function of cable elongation. The dotted lines are extrapolations.

Figure 6 shows the following results:

Beyond 1.4 m total cable elongation and 200 lb. tension load the cable exhibits tight buffer behavior. The fiber strain is 90% of the cable strain in this region. Elongation steps of 0.2 m did not result in noticeable strain relaxation during 5 min time intervals between steps.

Andrew FO-2. Elongation steps of 0.2 m, averaging 2 min apart in a 984 m length, showed immediate fiber strain and little strain relaxation. The fiber strain was 44% of the cable strain. This relationship was constant out to 8.4 m of cable elongation. There was no indication of tight buffer behavior.

A 22 min. waiting period at 4.2 m of cable elongation resulted in some fiber strain relaxation, about 9%.

Siecor FO-2. For cable elongation up to 4.0 m in a 984 m length, the fiber strain is 9% of the cable strain. Between 4.0 m and 7.0 m of cable elongation, the behavior gradually changes to that of a tight buffer tube. Beyond 7.0 m of cable elongation, the fiber strain is 90% of the cable strain, the same as Andrew FO-1.

A test conducted 16 hours after the above described test yielded very different results. With 0.6 m elongation steps averaging 12 min. apart, the fiber strain was roughly half that recorded previously and showed strain relaxation of about 15% during the time periods. However, attenuation and transmission measurements on other fibers did not indicate diminution.

Fiber failure

Short time fiber failure can be expected with increasing probability when the tensile stress approaches and exceeds the proof stress. The proof stress (or screen test) is performed on-line by Corning when it manufactures the fiber. There is a second type of tensile failure that occurs when the fiber is subjected to long term stress. Commonly called static fatigue, it is a function of time, temperature, humidity, stress level and maximum flaw size.

Andrew FO-1. The Corning lacquer coated fiber of 1980 manufacture was proof stressed to 25,000 psi. During the test, one fiber of the seven failed at 5.2 m of cable elongation and 610 lbs. The fiber stress for this condition was 48,000 psi. The failure was not surprising since the proof test was exceeded by 93%.

Andrew FO-2. The fiber has a composite protective coating (CPC), and was proof stressed to 50,000 psi by Corning. One of the eight fibers failed at 8.4 m cable elongation and 900 lbs. The fiber stress was 40,000 psi. The loading beyond 900 lbs. was restricted to the 1475 lbs. fast pull to prevent further failures.

No fibers broke during the fast pull to 1475 lbs. and 14.6 m of cable elongation. Strain data on the fiber being monitored indicated a maximum stress of 22,000 psi. The fiber stress for the same cable elongation under slow pull conditions would have been 70,000 psi. The reason for the low apparent stress level is unknown at this time.

Siecor FO-2. The fiber was Corning CPC proof stressed to 50,000 psi. None of the fibers failed during the slow pull to 10.8 m and 900 lbs. The fiber stress at that point was 52,000 psi.

Three fibers failed during the fast pull to 1475 lbs. and 17.4 m. One failed at 770 lbs.; the fiber stress was 58,000 psi. Two fibers failed at about 1300 lb. The tensile stress is unknown but certainly greater than 60,000 psi. All fiber failures were randomly spaced in the cable.

Attenuation and transmission

The attenuation and transmission measurements are summarized in Figs. 7, 8 and 9. A discussion follows.

Andrew FO-1. At cable tension below 150 lb. and 1 m elongation, there was negligible attenuation. Thereafter, attenuation increased rapidly and reached 2.5 to 8 dB at 200 lbs.

Upon a fast release of tensile load, the transmission would increase until a certain point and then go through a rapid cycle of decrease and increase. This transient is thought to be indicative of the fiber undergoing axial compression because the cable structure is contracting faster than the fiber. It was seen on all three cables.

Fig. 7. Relative attenuation as a function of cable tension. The Andrew FO-1 cable was manufactured under a 200 lbs. specification.

Andrew FO-2. Attenuation is negligible below 200 lbs. tension and 1.5 m elongation. The rise afterwards is roughly 0.5 dB per 100 lbs. of load.

Thirteen hours after reducing the tensile load from 900 lbs. to zero, fibers still showed about 1 dB excess attenuation and very slow recovery taking place.

The slow recovery characteristic was also noticed after the pull to 1475 lbs. and an 18 hour hold at 100 lbs. (Fig. 8)

Siecor FO-2. Attenuation is minor up to 200 lb tension and 2.5 m elongation. It is only 1 dB at 600 lb tension.

Transmission was greater than 95% up to 6.8 m elongation and 63% at 10.8 m elongation.

During the fast pull the transmission started increasing at 1000 lbs tension. The cable made a complete and rapid recovery after the release of tensions. (Fig. 4)

Increased time delay

There is an increase in transit time of a light pulse due to fiber elongation and stress-optical effects. These results are shown in Fig. 10.

Fig. 8. Transmission of the Andrew FO-2 cable during the fast pull test.

Fig. 9. Transmission of the Siecor FO-2 cable during the fast pull test.

Fig. 10. Delay time as a function of cable elongation.

Andrew FO-1. After 1.3 m cable elongation the rate of increased time delay is 3.5 ns/m. Up to 1.3 m there is no increased delay.

Andrew FO-2. The rate of increased time delay is 2 ns/m immediately upon applying tension to the cable.

Siecor FO-2. The rate of increased time delay is 250 ps/m up to 4 m cable elongation. Then it slowly becomes 2 ns/m.

Bandwidth

If strain is applied to fibers it has the effect of mixing and stripping modes. This is apparent when pulse shapes are studied as a function of tension. Figure 11 is an example of the impulse response of a relatively fast fiber with no tension on the cable. The precursor caused by the fiber index dip should be noted.

Figure 12 is the impulse response of the same fiber under 900 lbs. tension on the cable. Note that the precursor has disappeared, the frequency response has increased and the peak signal has decreased by 3.5.

Fig. 11. Impulse response of a cabled Corning graded index fiber under no tension. Note the precursor.

Fig. 12. Impulse response of a cabled Corning fiber under a 900 lbs. tensile load.

Figure 13 illustrates this change in bandwidth with tension for two fibers. The high bandwidth fiber changes less than 10%.

Fig. 13. Bandwidth of two fibers measured under tension during the slow pull test.

Cable Specifications

The results of these tests show that independent cable manufacturers can make cables to the same specification, which in turn exhibit different optical properties under tension. Our needs dictate that a cable can withstand substantial tensile shock and impact under tension without damage to the fibers or long term strain being imparted to the fibers.

From considerations of our requirements and these test data, a new set of specifications was written. Table 1 compares the pertinent old and new specifications.

Table 1. Old and new specifications

Property	Old specifications	New specifications
Fiber Number	6 - 8	3
Cable Diameter	< 16 mm	N/A
Temperature Range	Shipping/Storage -40°C to 74°C Operation/Installation -29°C to 85°C	-29°C to +74°C -20°C to +74°C
Gas block Pressure	125 psig - 24 hours	125 psig - 24 hours
Tension Test (100 m)	1506 lbs	405 lbs $\Delta t < 50$ ps $\Delta Att < 0.2$ db
Tensile Shock Test (100 m)	NONE	405 lbs in < 3 sec $\Delta t < 900$ ps $\Delta Att < 0.2$ db at 12 hours
Impact Test	200 impacts - 1 ft lb	157 lbs TENSION 10 impacts - 7.4 ft lbs $\Delta Att < 0.5$ db

Conclusion

We have demonstrated different optical transmission properties in two cables under tension. The cables were manufactured by Siecor and Andrews to the same specifications. These tests indicated that there were shortcomings in the specifications. A new set of specifications was written and sent to industry. The cables manufactured to the new specifications have just arrived so their characteristics cannot be reported here.

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