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Glass Optical Fibers for Harsh Environments

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Outline

- Goals and Scope
- Why FO now?
- Optic Fiber basics / types of Optical Fiber
- Potential types of Optical Fiber for Automotive
- Optical Fiber reliability in harsh environments
- MOST ® glass FO cables
  - Overview
  - Test Requirements & Results
- Summary

Goals/Scope

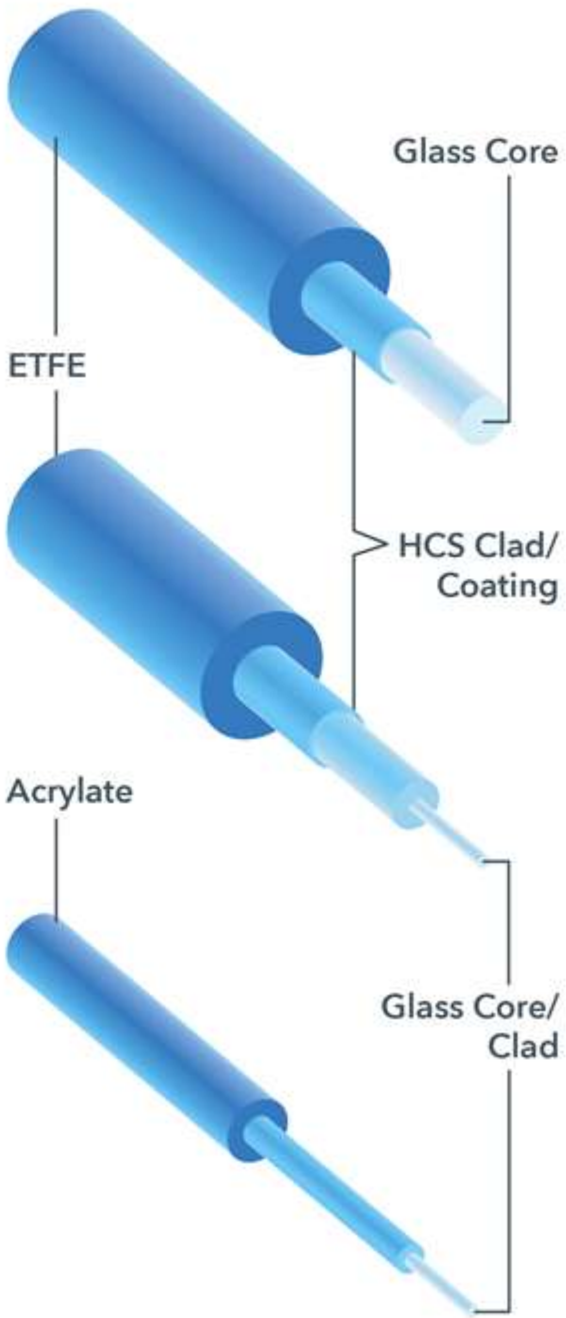
- Help lay foundation for optical cable objective by:
  - Providing tutorial of different optical fiber types
  - Show technical feasibility of optical cables in harsh environments
- Gauge interest for optical cable objective from broader ecosystem going forward to:
  - Address additional areas of technical feasibility for optical link
  - Address economic feasibility of optical link
  - Broad market potential of optical link
  - Gather OEM requirements for optical link parameters

Why Fiber Optics for Automotive?

- Requirement for more higher bandwidth and lower latency driven by:
  - Internal communications
    - Infotainment
    - Safety networks
      - Cameras
      - Sensors
    - Control
  - External Communications
    - GPS
    - Internet
    - Telematics
    - Vehicle to Vehicle
    - Vehicle to Infrastructure (Smart Highways)
  - Future Systems
    - ADAS
    - Autonomous driving systems
- Current requirements for as much as 10 Gbps
  - Roadmap for 25/40/50/100 Gbps and beyond
- Increase in EV vehicle systems requires EMI resistance
- Weight reduction and fuel savings

Types of Optical Fiber

- Step Index Multimode
  - POF - 1mm diameter PMMA fiber good for short distances, low data rates, benign environments, and easy termination; Bandwidth of >5Mhz-km @ 650nm, <1dB/m attenuation.
  - HCS - 125um to 1.5mm Glass core/polymer clad fiber made for moderate distances and data rates; rugged, durable and simple to terminate with hand tools; bandwidth of >5Mhz-km, <6dB/km attenuation at 850nm
- Graded Index Multimode
  - POF
    - PMMA: 400um to 1mm core sizes for higher speed communications over short distances in benign environments at 650nm; simple to terminate and align.
    - Perfluorinated : 10G up to ≤100mt (depending on type) in benign environments; simple to terminate, but small core sizes (50, 62.5, 120um) cause complexity
  - GiHCS - 50 and 62.5um core, 200um glass clad HCS fiber for 200 to 500 MHz-km bandwidth depending on size and wavelength; rugged, durable and simple to terminate with hand tools.
  - Glass - 50 and 62.5um core with 125um glass clad; bandwidth from 200 to 4700 MHz-km depending on type and wavelength; smaller core increases complexity of termination; requires fusion splicing, epoxy/polish, or laser cleaving for termination.
- Single Mode
  - Best bandwidth over longest distances
  - Small core makes termination, alignment, and cleanliness challenging
  - Less practical for automotive than Multimode fibers



Potential Glass Fibers for Automotive

200µm HCS Fiber with ETFE Buffer

Temperature: -65 °C to +125 °C
BW: ≥ 5 MHz-km @ 850 nm per IEC Standard
Attenuation: ≤ 6 dB/km @ 850 nm
Bend Radius: ≥ 16mm

GI HCS Fiber with ETFE Buffer

Temperature: -65 °C to +125 °C
BW: ≥ 400 MHz-km @ 850 nm (depending on core size)
Attenuation: ≤ 2.8 dB/km @ 850 nm (depending on core size)
Bend Radius: ≥ 16 mm

50/125 Standard GI Fiber

Temperature: -65 °C to +85 °C
BW: ≥ 4700 MHz-km @ 850 nm (depending on type and launch)
Attenuation: ≤ 2.2 dB/km @ 850 nm
Bend Radius: 17 mm

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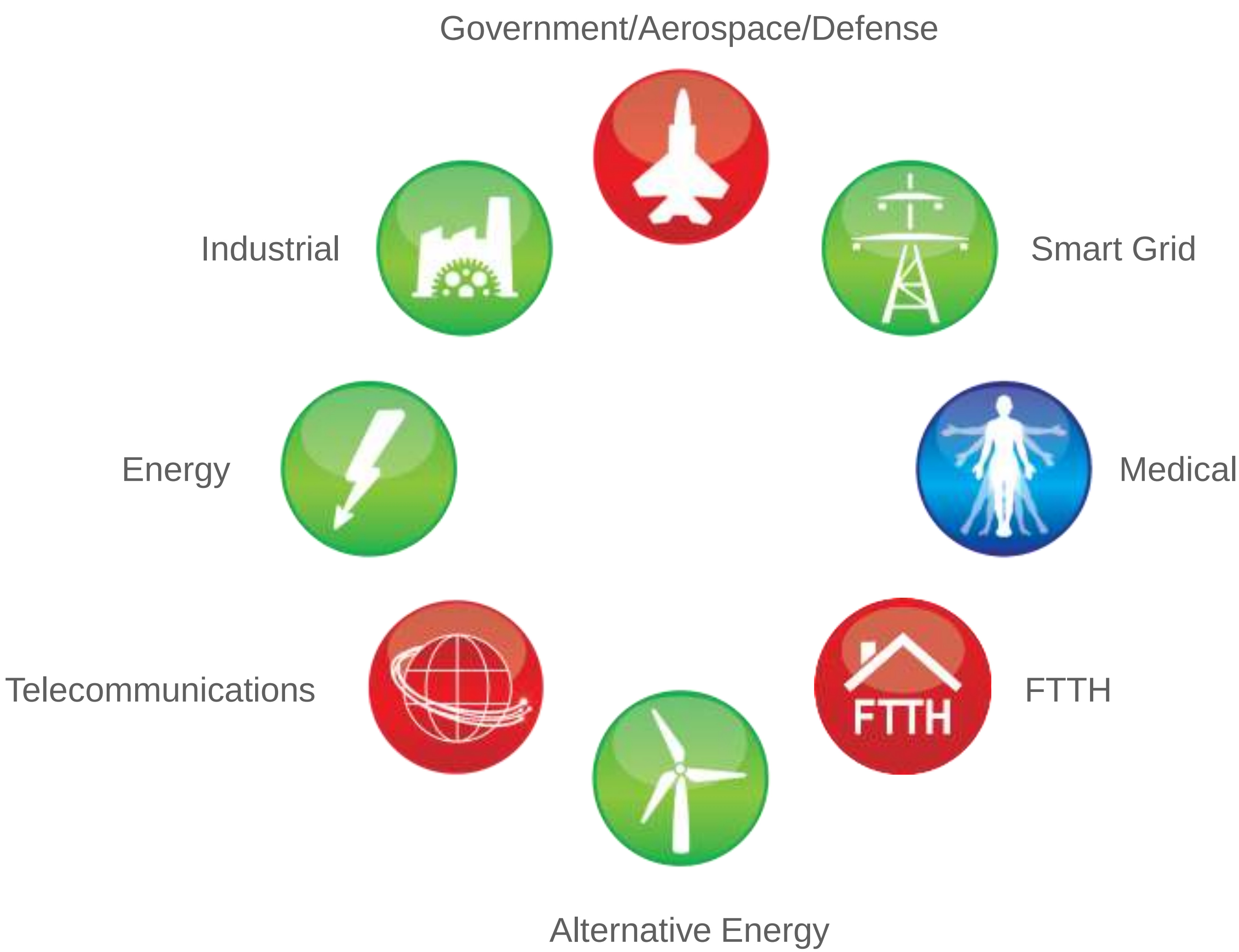
Glass Fiber Advantages vs POF

- Optical Characteristics
  - Step Index HCS usable at 650 and 850nm compared to POF at 650nm
  - Glass optical fiber has lower attenuation and greater BW than POF
- Thermal Characteristics
  - Glass fiber usable over a broader temperature range
- Mechanical Characteristics
  - Superior flexing performance
  - Superior tensile performance
  - Superior crush performance
  - Superior macrobending performance

Fiber Optics Have Penetrated Many Markets



Optical Fibers Thrive in Harsh Environment Applications

- Areas with challenging/harsh environments – temperature, chemical, EMI/EMC, mechanical, vibration, termination, flexing
- Addressed concerns about relative economics of fiber based solutions
- Fiber optic solutions provide alternate or complete replacement of copper solutions:

- Fiber to the Home
- Aircraft
- Oil and Gas wells – temperature and strain measurement
- Factory floor automation and robotics
- Tethers and umbilicals

Proven Reliability - Fiber Optics in Aviation

- First used in rigorous Military applications
  - Original data backbone on F-22, F-16 and F-18 variants, JSF
    - 100/140, OM1, OM2, OM3, and SM have all been used
  - Radio to antenna links in various airframes
    - Step Index HCS fiber cables used for decades
  - Retrofit in various airframe upgrades
- Initial commercial uses limited to non mission critical applications
  - In Flight Entertainment
  - Radio to antenna links
- Proven success is generating further commercial implementation
- 750km+ of cable expected to be used in 2016

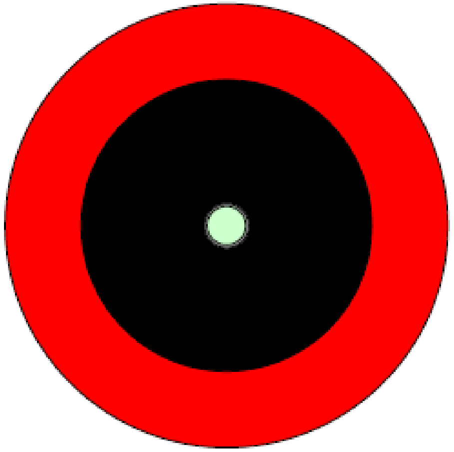
Aerospace Needs Similar to Automotive

- High reliability and long lifetime
  - 20+ years
- Wide operating temperature range
  - -55 to +125C for current commercial aerospace specs, higher for military
- Tight bends
  - 9mm bend radius
- Installation stresses
- Crush/clamping stresses
  - Resistance to microbending losses as well as mechanical damage
- Chemical resistance as a cable
  - Various oils, fuels, fluids, salt spray, etc
- Flammability
  - FAA, SAE, and OEM specific tests
- Smoke and Toxicity Issues
  - Low Smoke Zero Halogen an issue for applications in passenger areas

HCS Fiber and Automotive

- 200um Step Index HCS fiber was considered as the physical layer for MOST in the mid 2000's
  - Effort to change to VCSEL's required a change from POF
  - Work was done with a major OEM to create a performance standard and qualification plan
  - Qualification tests were executed. Final report never completed or issued
  - Decision was made to put off technology change to VCSEL based system
- IDB-1394 supplement for glass optical fiber
  - Included 200um Step Index HCS fiber cable
    - Performance specifications written, but no qualification work was done

MOST HCS Cable Design



Core Diameter 200 ± 4 µm

Clad
HCS®
230 +0/-10µm
Core/Clad Offset = $(S_{max} - S_{min})/2 < 5$µm

Buffer
PA-12 Black
1510 ± 40µm
Concentricity > 70%
Strippable $50N < F_{strip} < 70N$ with no clad damage over 30mm.
Pistoning with respect to core ±30µm

Jacket
Flame Retarded Polyolefin
2300 ± 70µm
Concentricity > 70%

Proofest 300 kpsi

HCS MOST Qualification Testing

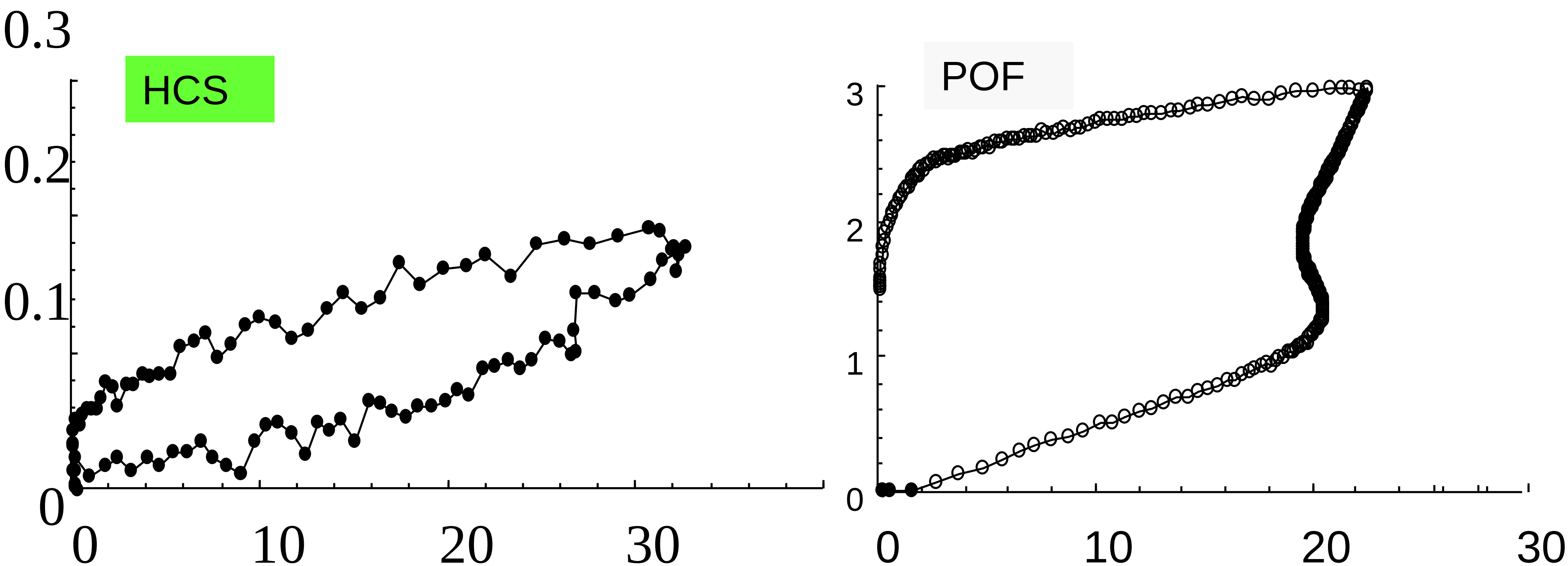
- Geometries
- Bandwidth
- Pulse Distortion
- Pistoning
- Flexibility
- Bending Radius
- Proof Test
- Flammability
- Static Bend
- Impact
- Tensile Strength
- Isostatic Pressure
- Static Torsion
- Cyclic Torsion
- Tensile Strain @ Bend
- Abrasion
- Thermal Aging
- Temperature Cycling
- Thermal Shock
- Chemical Resistance

Summary

- Demonstrated technical feasibility of glass FO in harsh environments:
  - Aviation
  - MOST Automotive
- Data requirements in future automotive platforms will continue to rise as more and more communication (both within and without the automobile) is required
- Autonomous driving concepts will only push this demand higher
- Glass optical fibers offer many benefits with respect to data rate, latency, and weight/space savings
- Glass optical fibers are a complementary technology that can be implemented alongside other technologies within automotive applications.

Appendix A: HCS vs POF Data

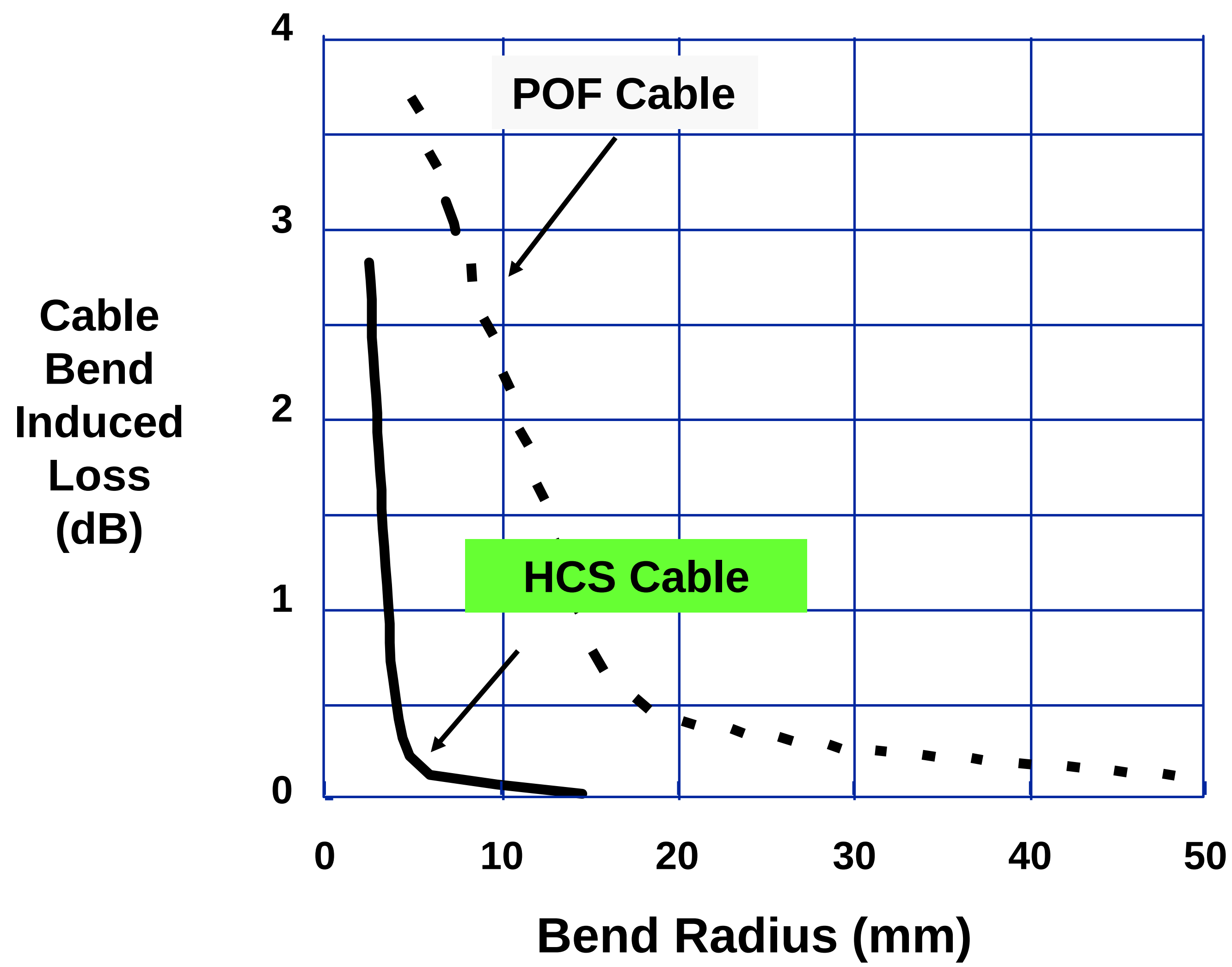
Tensile Load: HCS vs. POF



Attenuation Change (dB)
vs
Tensile Load (lbs) at 650nm

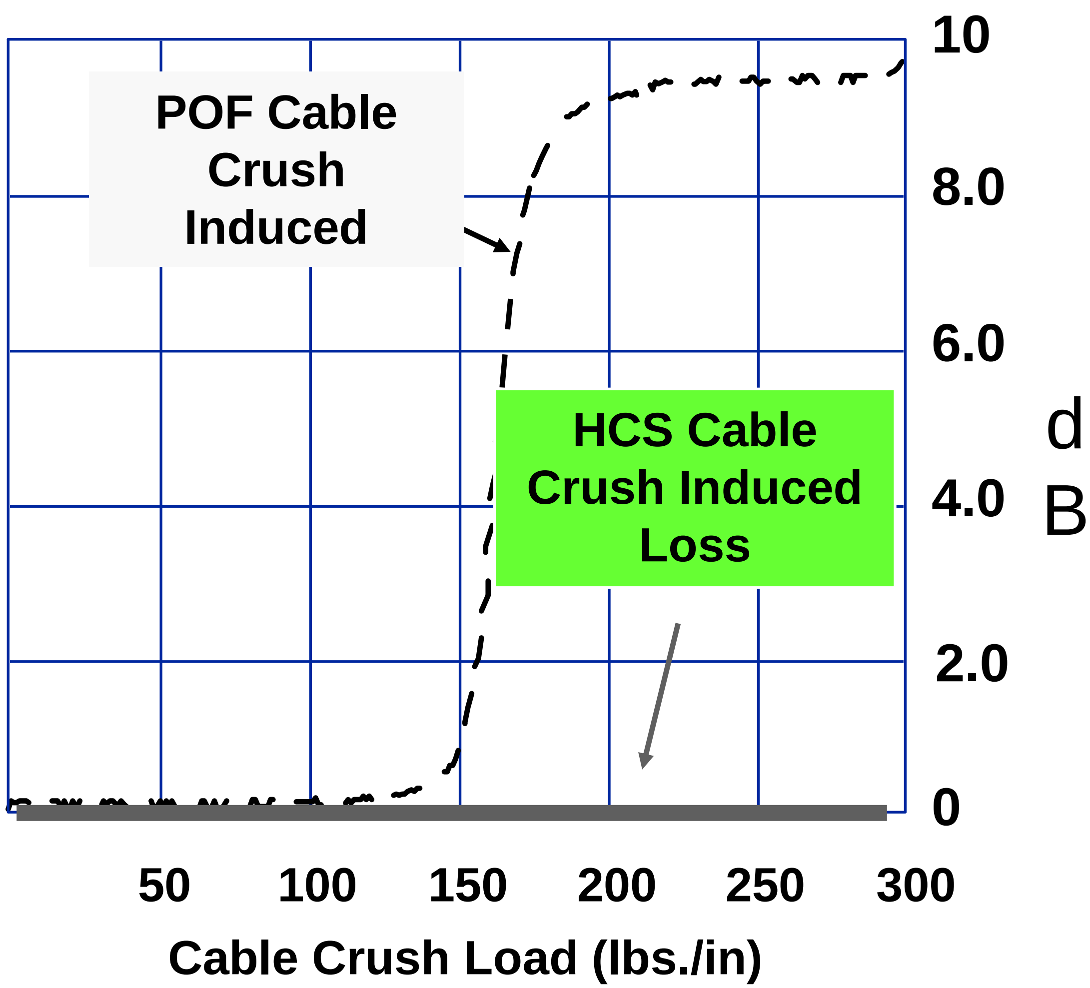
Attenuation under Bend: HCS vs. POF

- 180° Bend @ 650 nm

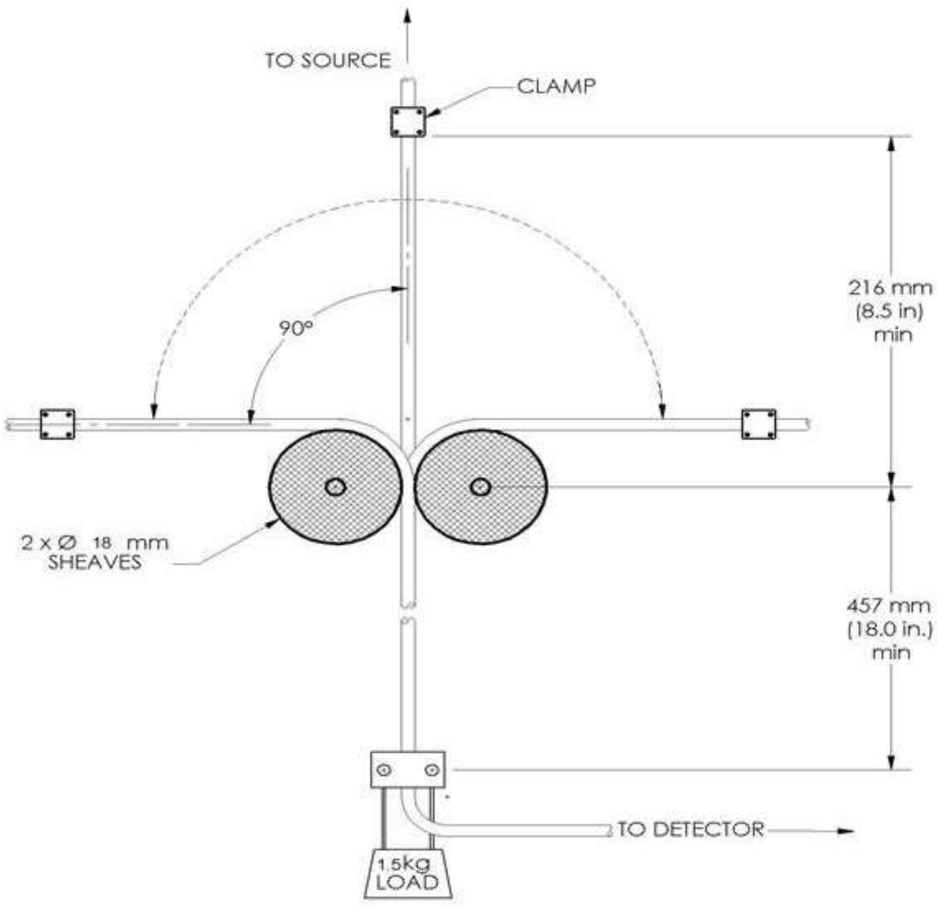


Crush Resistance: HCS vs. POF

Crush Induced Loss at 650nm



HCS vs. POF: Flexing

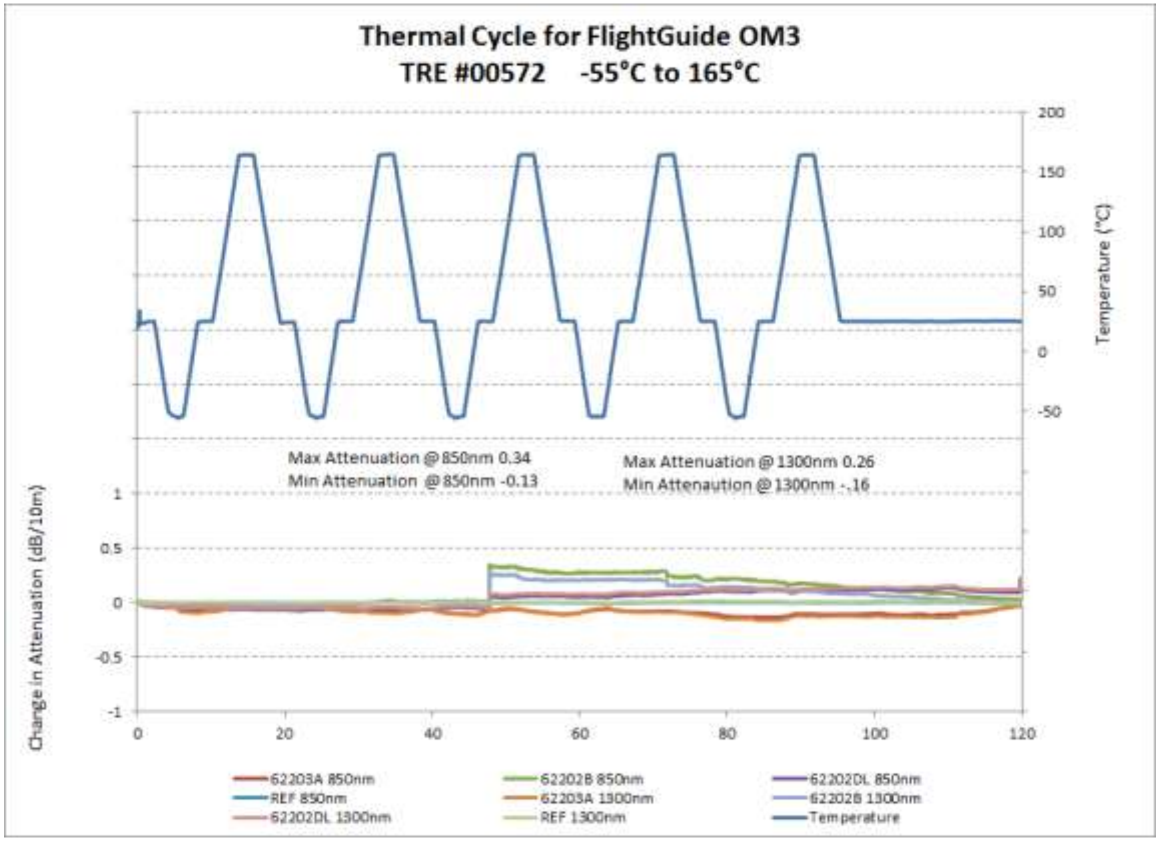


MOST 200um HCS Cable flexed 1,000,000 times with no change in transmittance. All 5 POF samples failed in 800-1700 cycles

Appendix B – Avionics Cable Test Results

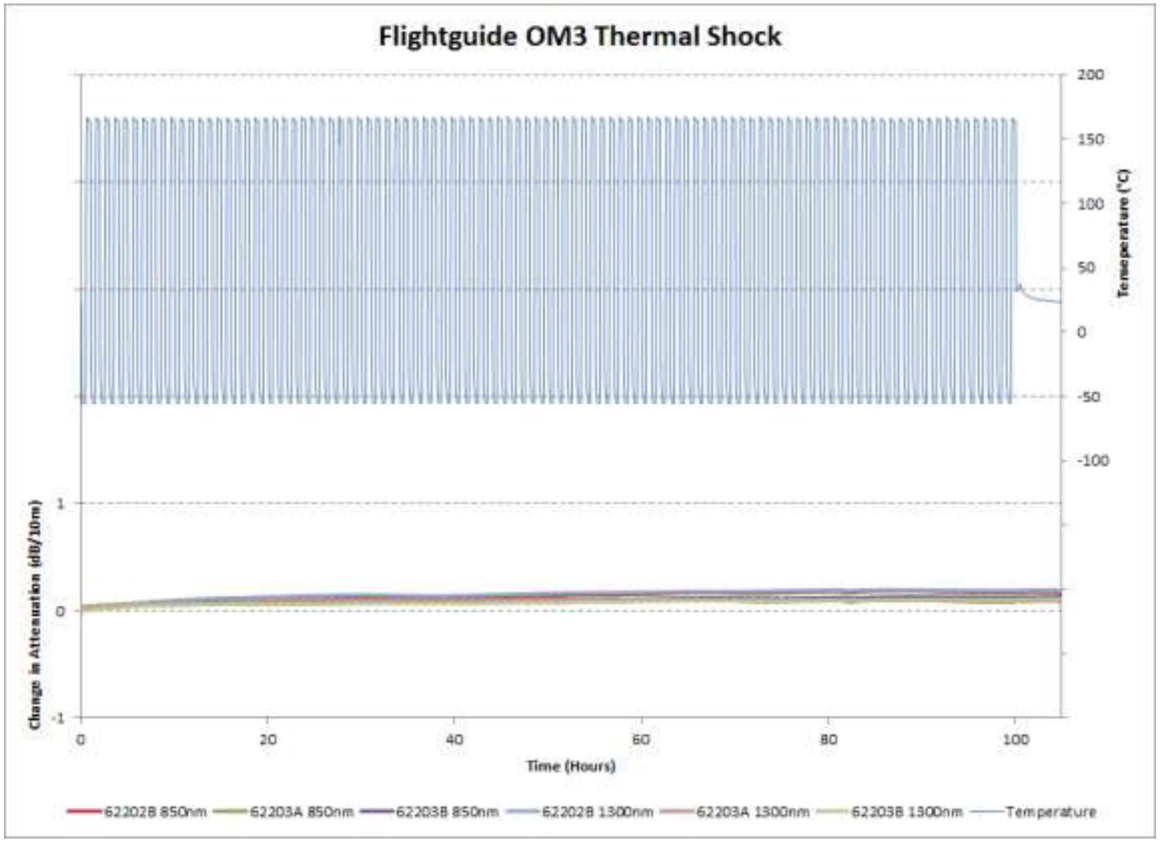
Thermal Cycling

This test was performed in accordance with FOTP-3. The temperature extremes were -55°C to +165°C for a total of 5 cycles. The dwell time at ambient and each temperature extreme was 1 hour. The sample lengths were 10 meters. Optical performance was monitored at both 850nm and 1300nm.



Thermal Shock

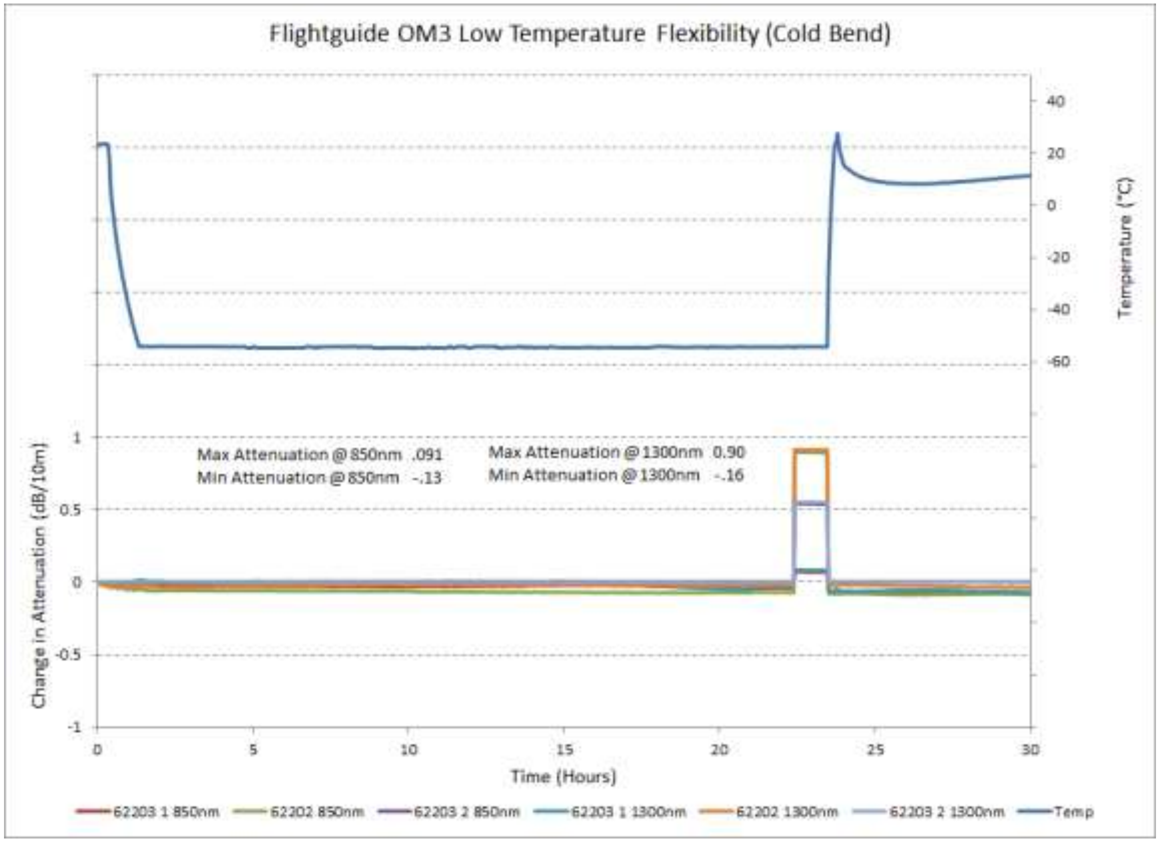
This test was performed in accordance with FOTP-3. The temperature extremes were -55°C to +165°C. One hundred cycles were performed with a 0.5 hour dwell at each temperature extreme. The sample lengths were 10 meters. Optical performance was monitored at both 850nm and 1300nm.



Permanent Change in Attenuation (dB/10m) after Test					
62202B 850nm	62203A 850nm	62203B 850nm	62202B 1300nm	62203A 1300nm	62203B 1300nm
0.17	**0.09**	**0.13**	**0.19**	**0.09**	**0.11**

Cold Bend

This test was performed in accordance with FOTP-37. The temperature used in this test was -55°C. The sample lengths were 10 meters and the mass used during the test was 2.5kg. After 22 hours at -55°C, the samples were wrapped four times around a 32 mm mandrel. The cable remained stationary for one hour after the mandrel wrap and was then returned to room temperature. Optical performance was monitored at both 850nm and 1300nm.



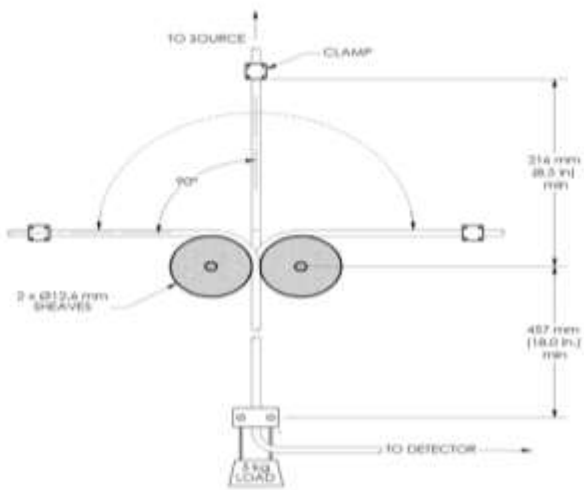
Cyclic Flex

Cyclic Flex was tested in accordance with FOTP-104 & CDT-22 at room temperature. Post-test change in attenuation was recorded at both 850nm and 1300nm after 10,000 cycles. The sample lengths were 10 meters. The mass used in this test was 5.0 kg.

Mass= 5 kg
Sheave dia. = 12.60mm
30 cycles per min. test speed

Sample	Change in Attenuation (dB) After cycles	
	850nm	1300nm
62202B	-0.11	-0.11
62203B	-0.36	-0.26
60223A	-0.03	-0.2

Sample	End of test visual Inspection
1	Pass
2	Pass
3	Pass

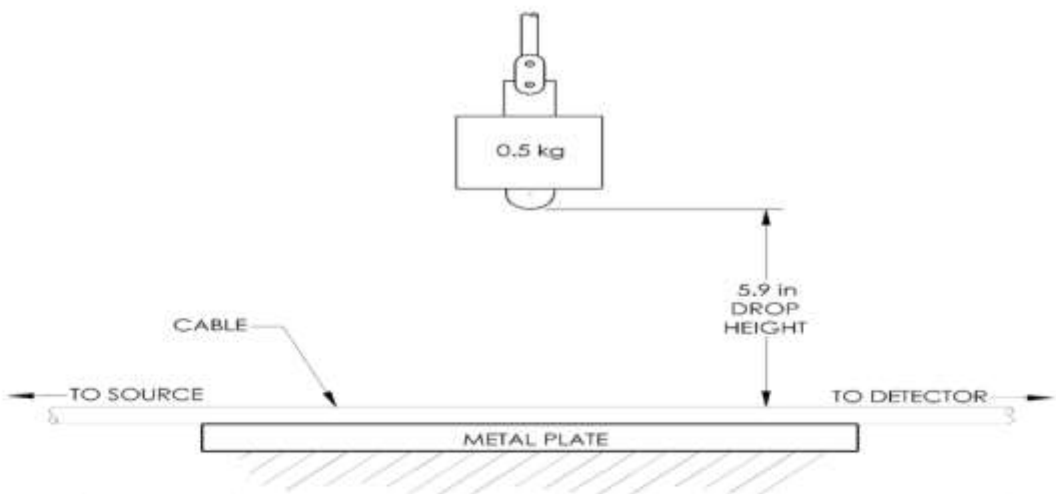


Impact

Impact testing was tested in accordance with FOTP-25 & CDT-10 at room temperature. The sample lengths were 10 meters. Optical performance was recorded at both 850nm and 1300nm at the end of the test. A mass of 0.5 kg was dropped from a height of 5.9 inches. A total of 50 impacts (military parameters) were performed per sample.

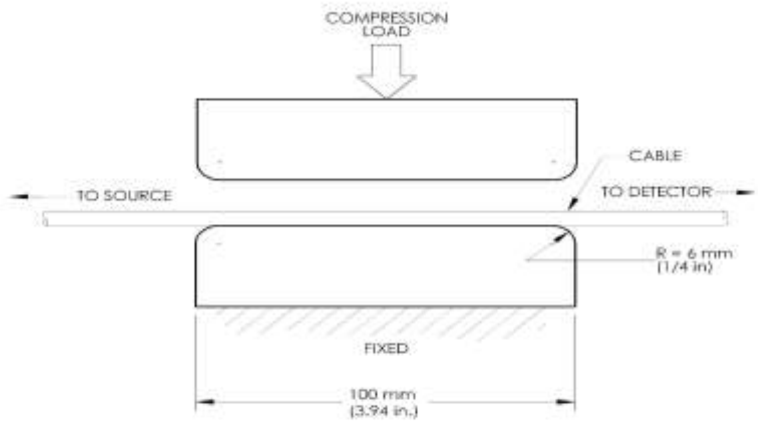
Impact Test (military parameters)

Sample	Number Of impacts	Change after Impacts @ 850nm (dB)	Change after Impacts @ 1300nm (dB)
602202DL	50	0.04	0.03
62203A	50	0.01	0.01
62203B	50	0.04	0.04



Compression

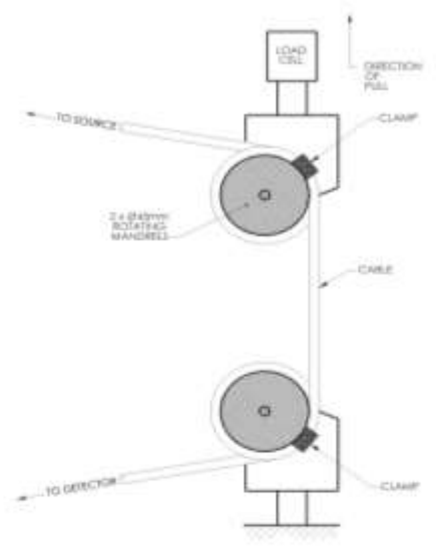
Compression testing was tested in accordance with FOTP-41 at room temperature. The sample lengths were 10 meters. A 10 meter cable sample was mounted horizontally in the test fixture. The load was applied in 500 lb. increments every 120 seconds until a max of 4500 Lbs. was reached. The load was then returned to zero. The attenuation was recorded at both 850nm and 1300nm at each load and then at zero load. The plate is 100mm with 6mm rounded edges.



	Change in Attenuation (dB/10m) with Applied Load (lbf)					
	62202B		62202DL		62203A	
Load (lbf)	850nm	1300nm	850nm	1300nm	850nm	1300nm
500	-0.02	-0.01	0	0	-0.01	0
1000	-0.01	-0.01	0	-0.01	-0.01	0
2000	-0.02	-0.01	-0.04	-0.03	-0.04	-0.03
3000	-0.06	-0.05	-0.05	-0.04	-0.11	-0.1
4000	-0.08	-0.09	-0.06	-0.05	-0.13	-0.12
0	-0.01	-0.02	-0.01	0	0	0

Tensile Loading and Bending

Tensile Loading and Bending in performed in accordance with FOTP-33. This test is performed at room temperature. The 10 m cable sample was mounted vertically in a tensile testing machine with upper and lower mandrels. The mandrel diameters are 45 mm. The cable was loaded in 50 N increments up to a maximum load of 600 N. The attenuation was monitored at both 850nm and 1300nm. The change in attenuation from zero load condition was recorded at each applied load. The sample was held for a period of one minute at each load. At the end of the test, the load was returned to zero and the final attenuation measurement was recorded.



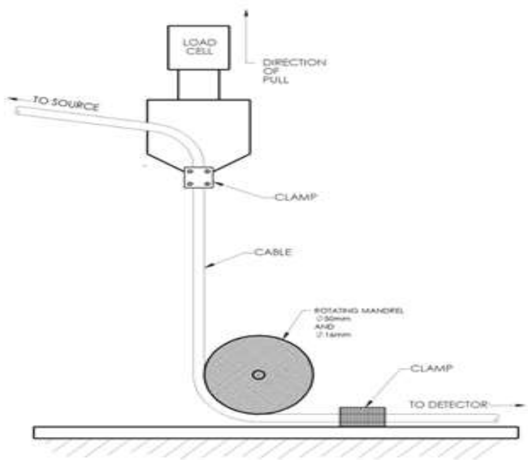
Change in Attenuation (dB/10m) with Applied Load (N)

Load (N)	Cable Lot Number					
	62202B		62202DL		62203A	
	850nm	**1300nm**	**850nm**	**1300nm**	**850nm**	**1300nm**
50	0.02	0.01	0.00	0.00	0.01	0.00
100	0.02	0.01	0.01	0.00	0.02	0.01
150	0.03	0.01	0.00	0.00	0.01	0.02
200	0.02	0.02	0.01	0.00	0.01	0.00
250	0.03	0.02	0.01	0.00	0.01	0.01
300	0.03	0.02	0.01	0.01	0.02	0.01
350	0.03	0.02	0.01	0.01	0.02	0.02
400	0.03	0.02	0.01	0.01	0.03	0.02
450	0.03	0.02	0.01	0.01	0.03	0.03
500	0.03	0.02	0.01	0.01	0.03	0.02
550	0.03	0.02	0.02	0.01	0.03	0.02
600	0.03	0.03	0.02	0.01	0.04	0.02
0	0.02	0.01	0.01	0.01	0.01	0.00

Bending Resistance

Bending Resistance was performed at room temperature in accordance with FOTP-88 at room temperature. Two different test set-ups are used to simulate conditions during cable installation and long term conditions after installation is complete. A 400 N load was applied to the 10 m cable sample for one minute, and then the load was removed. The cable was wrapped around a 50 mm diameter mandrel during the test. A 133 N load was then applied to the same cable test specimen while wrapped around a 16 mm diameter mandrel. The load was removed after one minute. Attenuation was monitored at both 850nm and 1300nm. The change in attenuation at each load condition was recorded.

Change in Attenuation (dB/10m) with Applied load												
Cable Lot No.	25 mm Bend Radius						8 mm Bend Radius					
	0 N		400 N		0 N		0 N		133 N		0 N	
	850nm	1300nm	850nm	1300nm	850nm	1300nm	850nm	1300nm	850nm	1300nm	850nm	1300nm
62203A	0	0	0.01	0.01	0	0	0	0	0.01	0.01	0	0
62202DL	0	0	0.01	0	0	0	0	0	0	0	0	0
62203B	0	0	0.01	0	0.01	0	0	0	0.01	0.01	0.01	0.01



Appendix C – MOST HCS Testing

Resistance to Bending

Purpose

Measure gradient of force over distand (flexural strength)

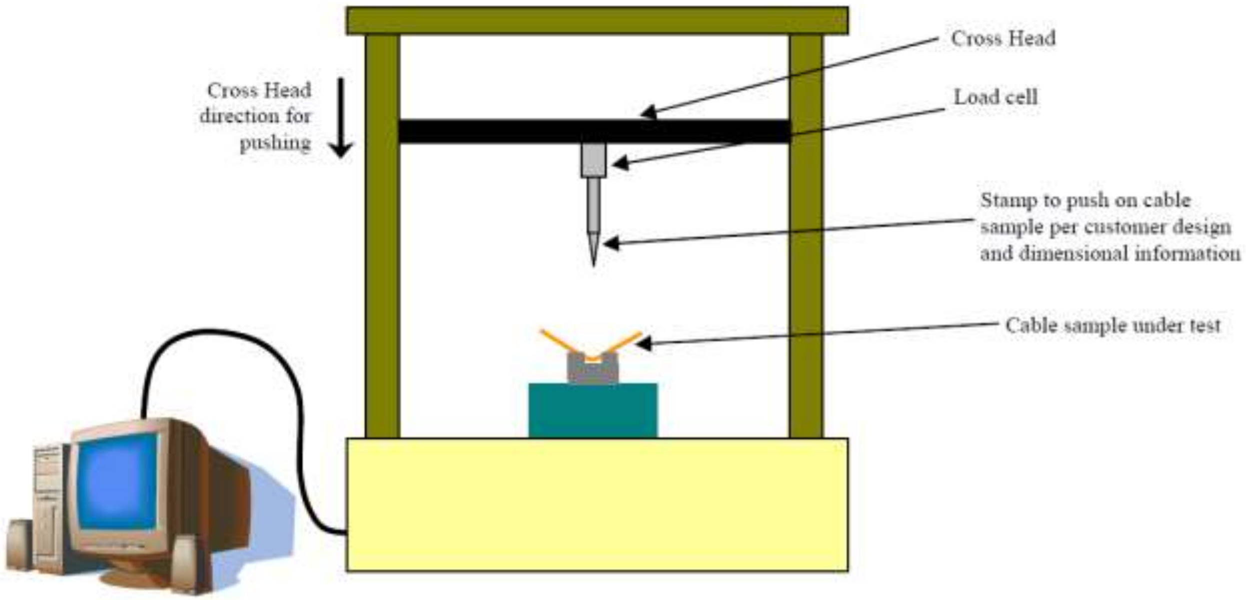
Test Procedure

asdAdapted from DIN EN ISO 178. Lay optical waveguide in the slot on the apparatus (part 1). The stamp (part 2) must hit the inside of the impressed bend. The cable may need to be held in position until the pressure of the stamp makes this unnecessary.

The increase of force over the bending distance (d F / d s) in the elastic range (from point of contact of the stamp to the cable (=0mm) to 0.3mm deformation length) is taken as the result.

The evaluation should be made using the sum of the smallest error squares. The calculation should be based on at least 20 measurement values.

Length of optical waveguide: l = 100 mm
Impressed bend radius: r ≥150 mm (due to beddi
Draw speed: v_{pull} = 5 mm / min
Climatic: RT = 23°C



Bending Radiuses

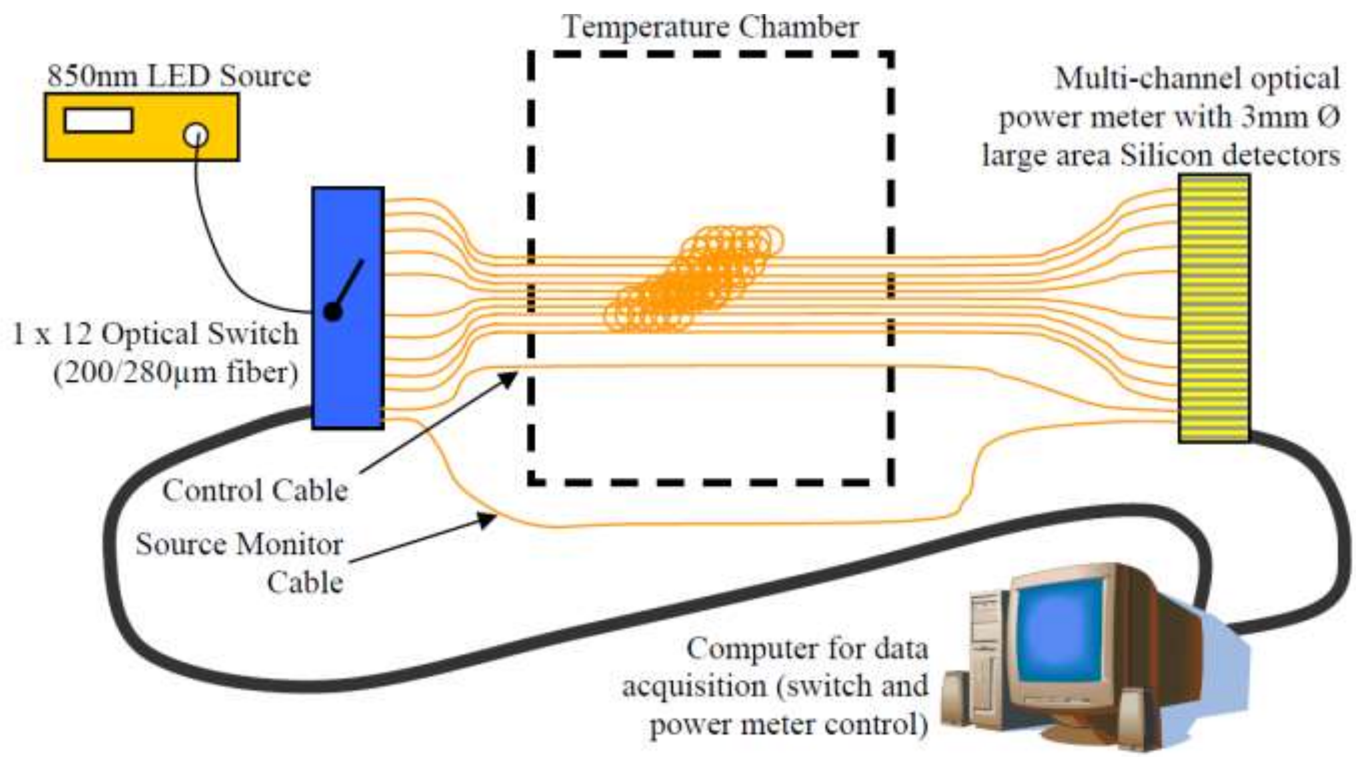
Purpose:

Measure long term stability for static bending of cable.

Test Procedure:
Statically bend the optical waveguide in the middle of the optical cable by applying 10 windings around a 9mm radius mandrel. The method of fixing must not damage the optical waveguide or affect the measurement. Winding tension should be < 5N.

Subject the cables to T= 85ºC, RH = 85% for 1000 hrs, followed by Drying Period of T= 85ºC, RH < 50% for 96 hrs, followed by Cooling Period of RT= 23ºC, RH < 50% for 24 hrs.

Measure attenuation change over time using



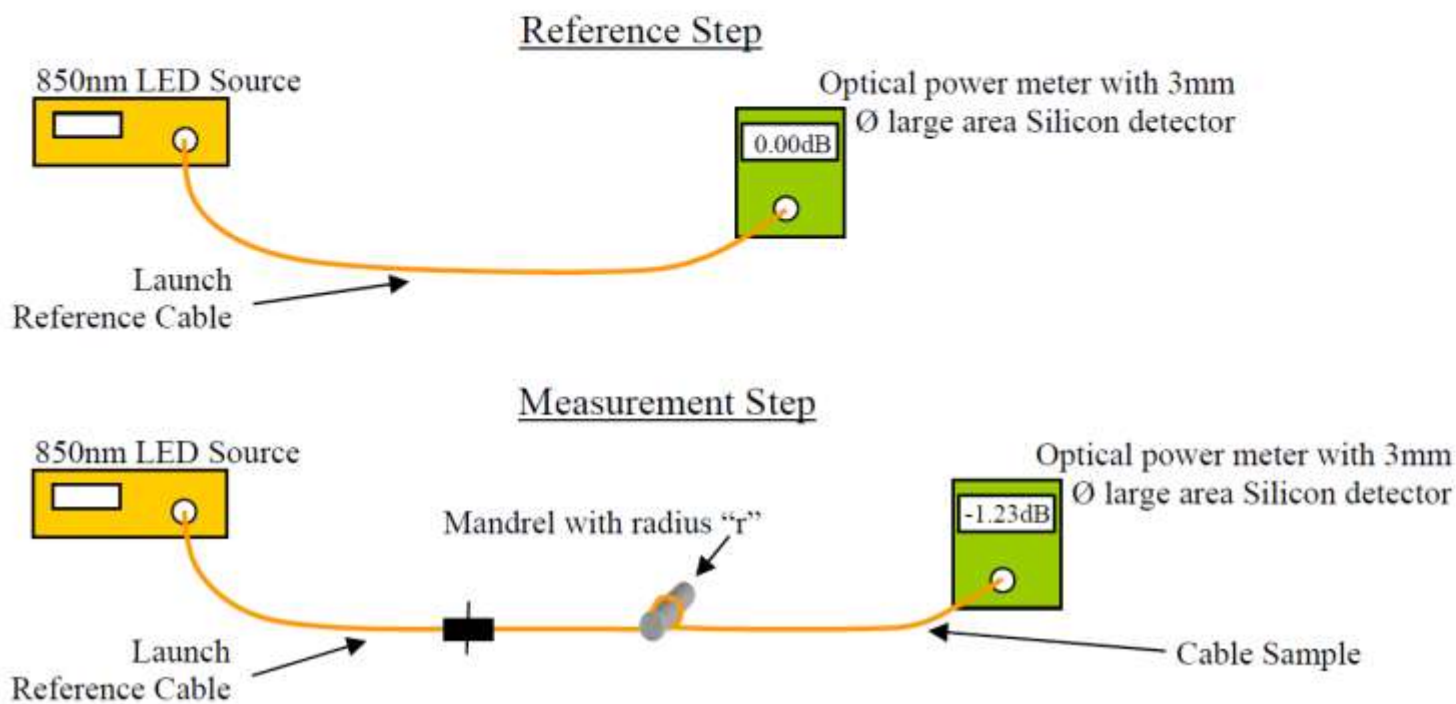
Static Bending

Purpose:
Measure reversible attenuation change due to static bending of new samples and aged samples.

Test Procedure:
See IEC 60794-1-2 E11

Statically bend the optical cable at the midpoint of its length through an angle of 360° around a mandrel of the respective diameter (r_x). The method of fixing must not damage the optical waveguide or affect the measurement. After bending the optical cable must be returned to relaxed position and measured again.

Parameters:
Temperature: T_1 = RT (23°C)
T_2 = -20°C
Bend Radii: r_1 = 15mm
r_2 = 13mm
r_3 = 11mm
r_4 = 9mm
r_5 = 7mm
r_5 = 5mm



Impact

Purpose:

Measure optical attenuation with respect to impact resistance of optical cable

Test Procedure:

Optical attenuation with respect to impact resistance was measured for six samples. Three were tested at ambient temperature and three were tested at -20C. The impacts were applied by releasing a 100g, 12.5mm hemispherical hammer from a height of 100mm. Each sample underwent three impacts at different locations on the cable. Optical power was recorded before, during, and after each impact at a sampling rate of 1kHz.

Impact test setup at -20C

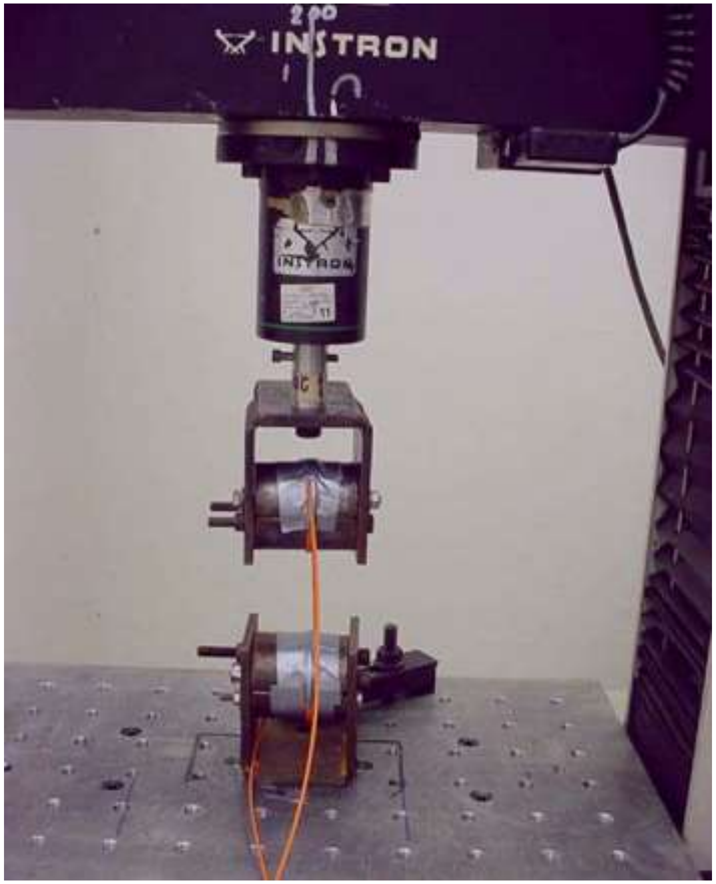
Tensile Strength

Purpose:
Measure optical attenuation and elongation in dependence of the tensile strain on the optical cable.

Test Procedure:

See IEC 60794-2-40.   The method of fixing must not influence the attenuation measurement

Parameters:
Length of sample subjected to tensile stress: l_{pull} = 0.2m (straightened)
Temperature: T_1 = RT (23°C), T_2 = 85°C
Pull Speed: v_{pull} = 10 mm / min



Isostatic Pressure

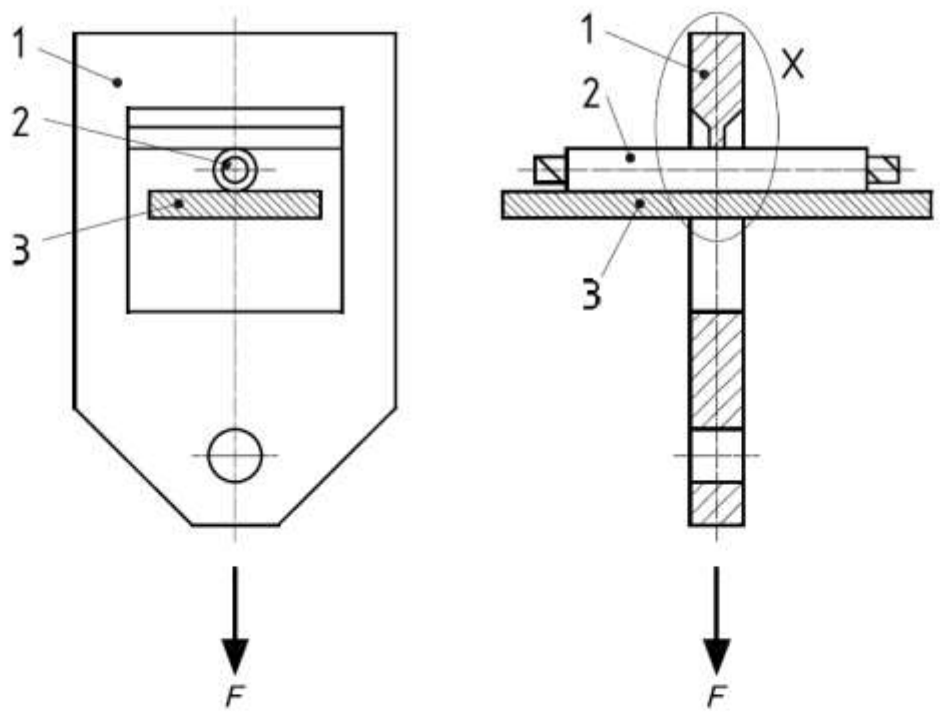
Purpose:

Measure of optical attenuation in dependence on the thermal pressure.

Test Procedure:

Probe Used: per ISO 6722, Measurement procedure without high voltage testing.

Parameters:
Test Weight: For T_1 = RT (23^{o}C), F_1 = 70N
(Time at T_1, F_1 = 4hrs)
For T_2 = 125^{o}C, F_2 = 13.5N
(Ramp up to T_2 from RT = 2 K/min, Time at T_2, F_2= 4hrs)



Isostatic Pressure with Humid Thermal Stress

Purpose:

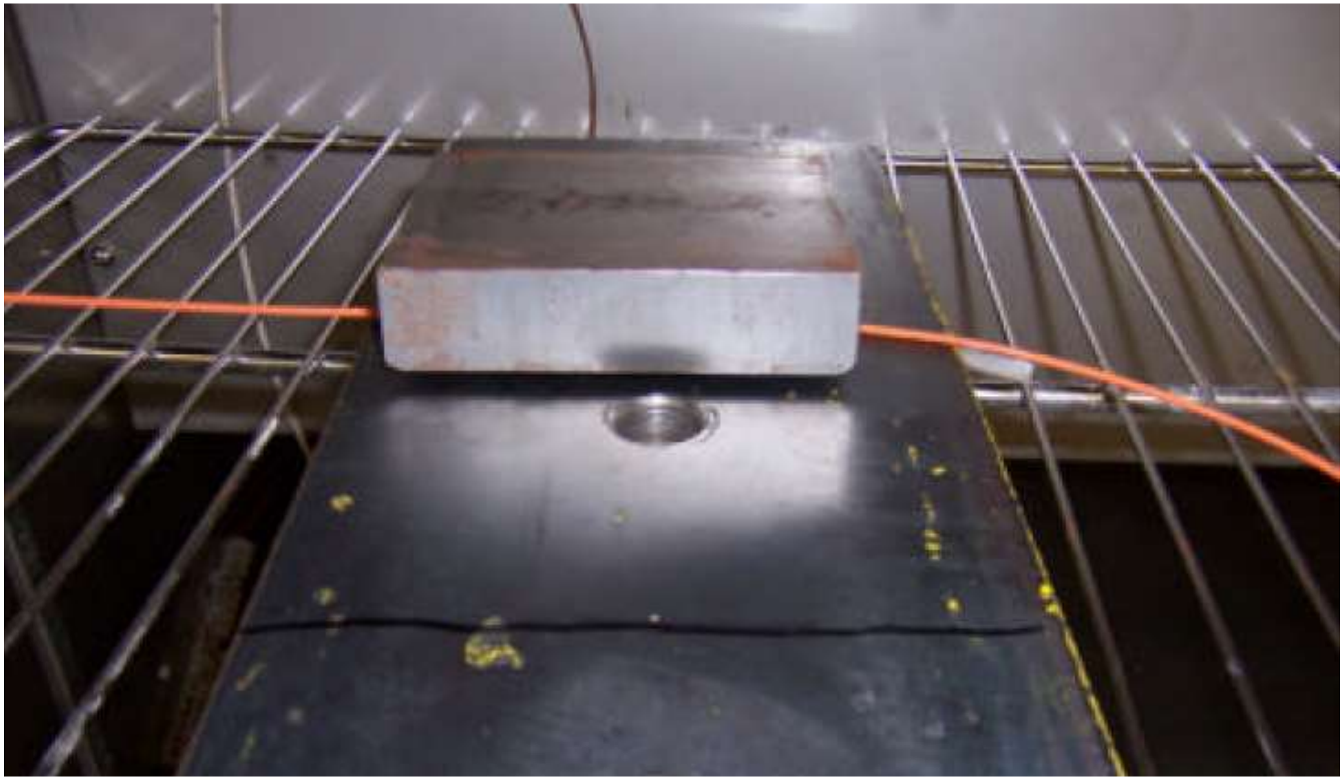
Measurement of the optical attenuation depending on lateral compression under high air humidity.

Test Procedure:

Set-up see IEC 60794-1-2 E3

1. Store optical waveguide at specified temperature and humidity 240 h without test weight.
2. Store optical waveguide at specified temperature and humidity 240 h with test weight.
3. Store optical waveguide at specified temperature and humidity 240 h without test weight.

Test weight: F = 50 N



Static Torsion

Purpose:

Measure of optical attenuation in dependence on a static, continually increasing torsional stress placed on the optical cable

Test Procedure:

Six samples were tested at ambient temperature and, six were tested at -20C, and six were measured at 125C. Each sample oriented in the axial direction and fixed to the torsional stress aparatus such that the attenuation was not affected. The twisted length of each sample was fixed at 0.2m and twisted to a maximum of 720 degrees over 1 hour. Each sample then untwisted at a constant rate over a 1 minute period. Optical power was recorded once per minute.

Dynamic Torsion

Purpose:

Measure optical attenuation in dependence on a dynamic torsional strain placed on the optical cable, whereby the optical cable is twisted in oscillation in both directions about its original position

Test Procedure:

Six samples were tested at -20C. Each sample was oriented I the axial plane and fixed such that the attenuation was not affected. Furthermore, 500g of torsional strain was applied at one end of the sample. Each sample underwent 10,000 cycles at 1 cycle per 2 seconds, where one cycle involved twisting from the starting position at 0 degrees to +270 degrees, back through 0 degrees to -270 degrees and back to 0 degrees. Optical power was measured every 500 cycles.

Tensile Strain and Bend

Purpose:

Measure reversible attenuation change due to static bending of new samples and aged samples.

Test Procedure:

See IEC 60794-1-2 E18. The method of fixing must not influence the attenuation.

Parameters:

Length subjected to tensile strain: l_B = 1 m (straightened)

Temperature: T_1 = RT (23^{o}C)

Bend radius (mandrel): r = 9 mm

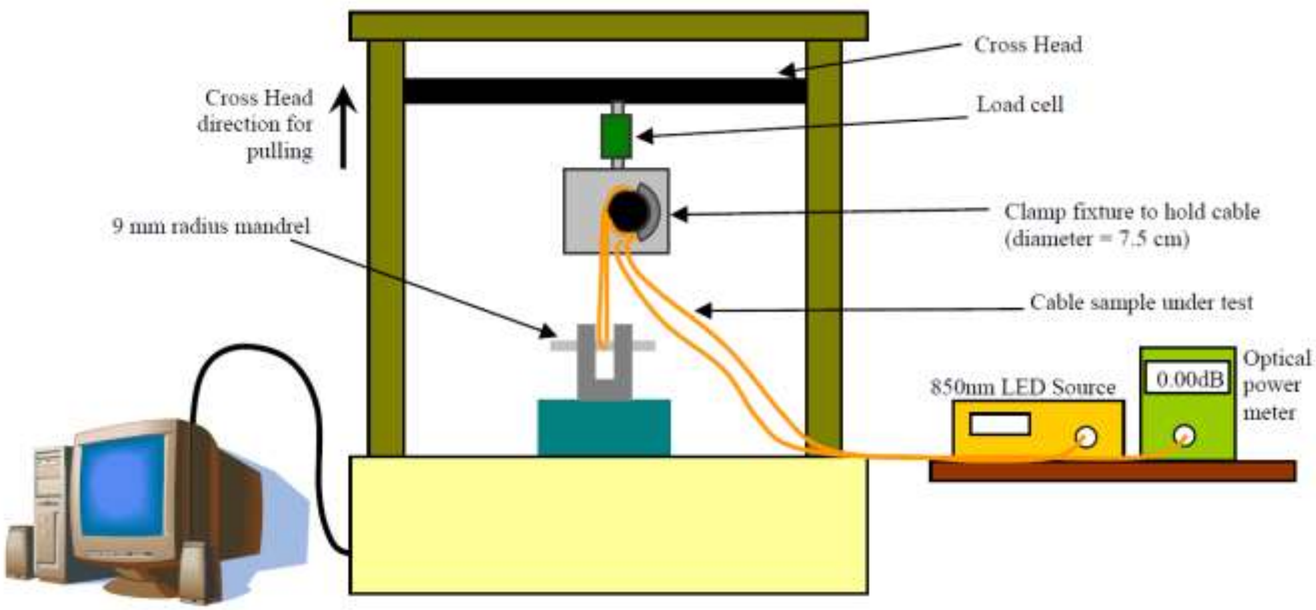
Angle of bend: 180°

Bending position: in the centre of I_B

Tensile force at bending point: F_1 = 30 N F_2 = 60 N

Note: F_X = ½ F_{actual}, when both ends of the optical cable are fixed.

Duration of strain: t = 60 min.



IEC 60794 1-2 E6, Repeated Bending

Purpose

Measure change in optical attunation in [dB] over bending cycles at various temperature conditions.

Test Proceedure

Repeated Bending

Change in optical attenuation was measured over bending cycles. Ten samples were tested at ambient room temperature (21°C-25°C), and another ten samples were tested at -20C. The bend radius of the mandrel was 12 millimeters, while the bend radius from the clamping mechanism of the optical cable to the bending point was fixed at []. Each sample underwent 100,000 cycles at 1 cycle per 2 seconds. , where one cycle involves bending from the starting position at 0 to +90, back through 0° to -90°, and back to 0. Optical power was measured once every 8.5 minutes.