Fiber Optic Cable

Application Note AN-3016
Mechanics of Metallic Cable Structures for Downhole Optical Fiber Applications

ABSTRACT

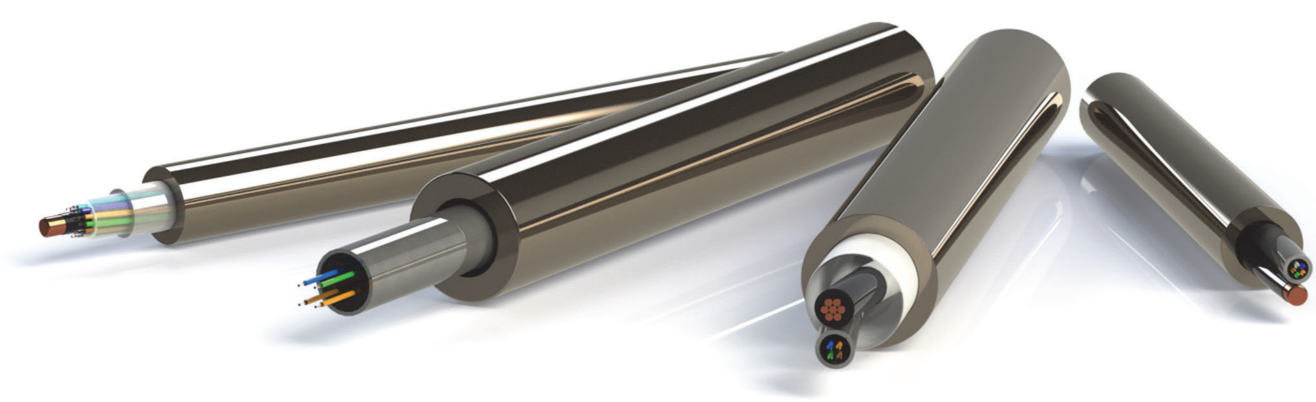
This application note provides an overview of the importance of material selection for oil and gas applications involving high temperatures in conjunction with various mechanical loadings. This highlights key areas such as metallurgy of conditioned materials, optical fiber and component interactions, and mechanical performance of metallic cable structures at elevated temperatures in conjunction with a design factor of safety. Units are primarily in Imperial format. It should also be noted that the material presented in the publication is intended as general information; for design purposes it is recommended that reference be made to appropriate standards and specifications, such as those prepared by authoritative organizations such as the American Society of Mechanical Engineers (ASME), the American Society for Testing and Materials (ASTM) and the American Petroleum Institute (API).

INTRODUCTION

Whether the application is in the realm of downhole completions, surface pipeline monitoring, or refinery process analysis and characterization, the majority of initial application considerations and performance requirements are driven by having assumed the temperature and mechanical loading expectations of the respective operating environment. Engineering a system adequately to these variables can be the difference between premium system performance and a system that does not meet the specified optical performance criteria, and as a result fails to adequately function.

As temperature increases material properties change. As an example, upon comparison of the thermal expansion coefficients of silica optical fiber and 825 Incoloy, there is a significant difference, which if not accounted for, can be a potential mode of system failure. Many aspects are factored into an optical cable design that effectively mitigate risks associated with this thermal elongation phenomenon. For the purpose of this application note the focus will be narrowed to two major contributors, *EFL* (excess fiber length) and *thixotropic gel fluid*.

A factor of safety (FoS) is a term commonly used to describe the capacity of a system below the expected or actual applied conditions and in this context it is to be taken as a material performance threshold. When defining the temperature requirements of a system it is a common practice to apply a performance FoS to serve as a design limit that effectively helps to govern the risk of system failure. Case in point, if a bottom hole temperature is assumed to be 135°C it would be ideal to manage the probability of component failure by designing a system that can adequately function up to 150°C. This design directive would translate into a FoS of approximately 1.11 or about 11% threshold and result mitigated risk.



Downhole Optical and Hybrid Cable Designs

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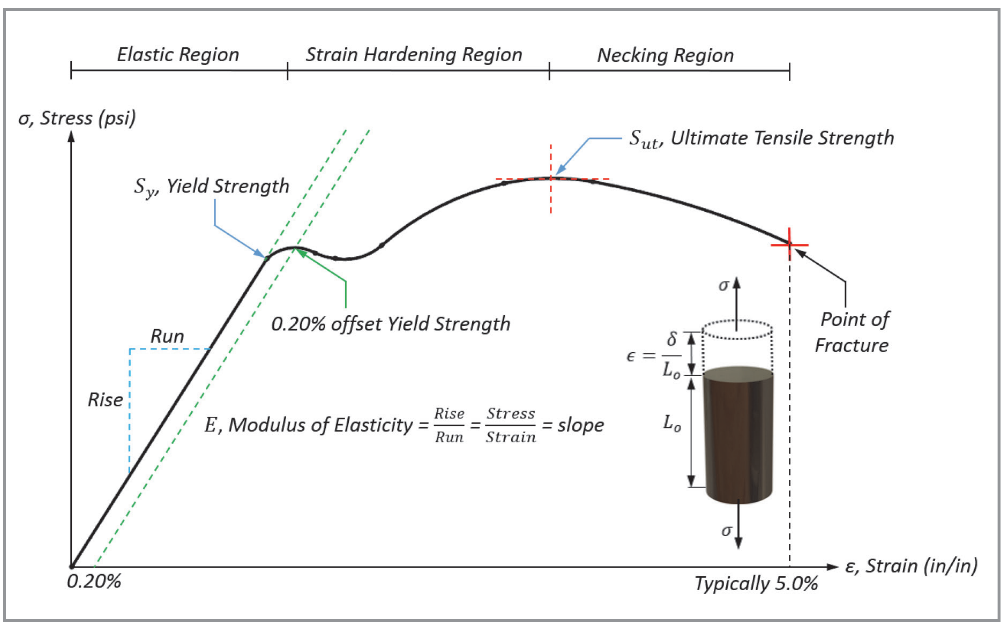
BASIC MECHANICS OF MATERIALS

In advance, it is beneficial to develop an understanding of the mechanics of materials. Below are principle terms that can be referenced including a relatable stress-strain graph, detailing the tensile behavior of a ductile material. The opposite of ductile would be brittle. Brittle materials tend to have high tensile load ability however they have limited elongation capacity and so tend to fracture as the loading reaches the elastic limit.

- ***S_y, Yield Strength (psi)*** Maximum stress that can be applied without permanent deformation of the material.
- ***S_{ut}, Ultimate Tensile Strength (psi)*** Maximum strength reached in the engineering stress-strain curve.
- ***E, Modulus of Elasticity (psi) (also called Young's Modulus)*** Ratio of unit stress to unit strain within the proportional limit of a material in tension or compression.
- ***δ, Elastic Longitudinal Deformation*** Change in original length L, of a material of cross-section area A, and modulus of elasticity E, under an axial force F.
- ***ε, Engineering Strain (Unit per Unit)*** Amount by which a dimension of a body changes when the body is subjected to a load, divided by the original value of dimension
- ***σ, Engineering Stress (psi)*** Average uniaxial force (tensile or compressive) per the original cross-sectional area.



Stress-Strain Graph of a Ductile Material

For a ductile material under tensile load the stress-strain response transitions linearly, this is known as the *linear elastic region*, when the loading is removed the material will elastically rebound to its original un-stressed length. In this region the *Modulus of Elasticity* ***E***, can be approximated based on the applied stress divided by the measured strain. The point at which the linear trend ends (the wavey section) is known as the material *yield strength* $\boldsymbol{S_y}$. In many testing standards, the *yield strength* of most metals is defined as the stress at which a line parallel to the linear modulus line, but offset from it by 0.2% strain, intersects the curve.[3] After the material is stressed beyond the elastic range, it then reaches the *strain hardening region*, producing materials that are permanently elongated, not returning back to their original un-stressed length, and simultaneously decreasing *ductility* while increasing *strength*. The peak of the curve is known as the *Ultimate Tensile Strength* $\boldsymbol{S_{ut}}$, or just the tensile strength. After this point the material response will transition into the necking region, nominal stress will decrease upon additional loading, and thinning will begin to concentrate near the region where the *point of fracture* will eventually occur.

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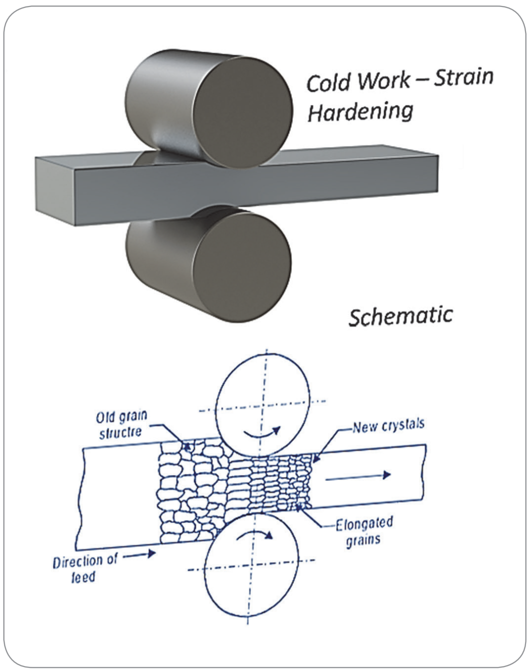
METALLURGICAL PERFORMANCE AT HIGH TEMPERATURES

Cold Work—Strain Hardening

Solid solutions of iron with alloying elements, like 316 Stainless Steel and 825 Incoloy, are identified as *Austenitic Alloys*. These materials are often conditioned to increase material strength and as previously mentioned, a common method of conditioning is *cold working or strain hardening*. In continuous metallic cable structures a cold work material conditioning method is often performed by inducing multiple stages of strain hardening below the material's recrystallization temperature which increases the point defect and dislocation densities of the material. AFL's method of material strain hardening is tuned and balanced to ensure optimal strength while maintaining ideal ductility. In the case of traditional downhole cables that utilize 825 Alloy tubing, the incoming materials are specified to a material condition that compliments the remaining process steps that inevitably decrease ductility and increase strength. During the tube making process, the strip is formed into a tube by a series of forming rollers to a point at which the edges are TIG (Tungsten Inert Gas) welded to produce a seam, and lastly the product is strain hardened or cold worked at which the final material condition remains compliant to the requirements of NACE MR0175. *MR0175/ISO 15156-3:2015(E) specifies a final material condition that is less than recommended surface hardness value of 40HRC (Rockwell C-Scale Hardness Number).*



Cold Working/Strain Hardening Schematic

Polycrystalline metal alloys such as the ones mentioned above contain grain structures with various grain diameters. Upon examination with an electron microscope of a cold worked material specimen the individual grains will be noted to have their own discrete orientations and slip planes.

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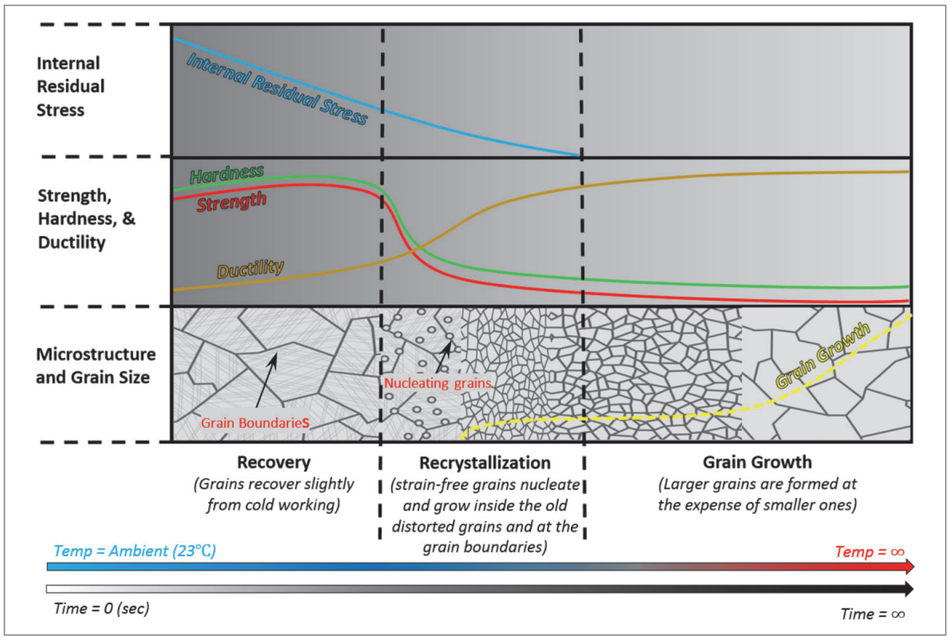
Microstructural Transformation Scenario: Post Cold Work Material Condition → Exposure to High Temperature

During the cold work phase the grains are dislocated or elongated which increases the material density or number of grains in a finite area thus increasing the strength of the material in said finite area. From a thermodynamic perspective, cold working these alloys increases the point defect density, dislocation density, and the energy used to plastically deform the material is stored as residual strain energy; the material effectively becomes a battery of energy in a microstructurally metastable state. A method for returning the grains to an equilibrium state is to *anneal* or expose to high heat for a finite amount of time, bringing the material above the recrystallization temperature; this is dependent on the percent of cold work incurred and material purity. During this exponentially time-dependent process the material will go through a series of thermodynamic changes:



Effects of Elevated Temperature on Strain Hardened Materials

- Recovery

  Grains recover slightly from cold working. Residing below the recrystallization temperature, this is where stored energy from point defects and dislocations is freed and polygonization occurs. This polygonization phenomenon involves dislocations of the same orientation arranging themselves in a low energy configuration and as a result crystal segments lying between a pair of low-angle boundaries approach the state of strain-free crystals with flat uncurved planes.

- Recrystallization

  Strain-free grains replace cold-worked grains.

  →*Obeying the 1st law of thermodynamics:* ΔU *(recrystallization)* $= U_d$ *(deformed material)* $- U_u$ *(undeformed material)*

  As temperature increases pre-existing strain free grains and new nucleated strain free-grains replace the cold-worked strained grains decreasing the internal residual energy of the grain dislocations. Primarily, recrystallization leads to an overall decrease in internal energy of the material by replacing deformed regions with strain-free regions; ductility is increased and strength is decreased.[2]

  – Cold work increase leads to decrease in recrystallization temperature, and Increase in metal purity increases rate of recrystallization.

  – The rate of recrystallization is an exponential function of temperature. But, since the process is a complex combination of many processes, the activation energy for recrystallization cannot be recognized as a fundamental constant.

- Grain Growth

  Larger grains are formed at the expense of smaller ones, leading to the increase in the average grain size. Grain growth is driven by atomic bond maximization. Due to larger curvature of smaller grains an atom at the grain boundary is bonded to less number of surrounding atoms, while a similar atom on a larger grain boundary is bonded to more atoms. The system can lower its energy by the jump of an atom from the smaller grain boundary to the larger grain boundary.

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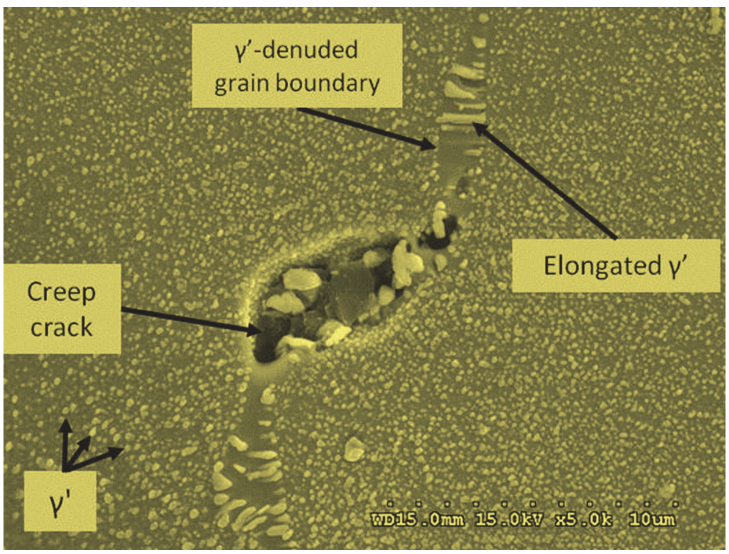
Accounting for Recrystallization Temperature

High temperature service applications such as 300°C require the selection of materials that have a relatively high recrystallization temperature so to not deduct from any of the desired and incurred strength acquired from cold working. As previously mentioned, the recrystallization temperature of a material is related to melting temperature as well as other factors like amount of cold work and material purity. It is challenging to approximate for the recrystallization temperature of materials like 316L Stainless steel and Nickle Alloy 825. One way is by using the melting temperature of Austenitic 316L SS, approximately 2500°F (1370°C), in conjunction with the rule of thumb that recrystallization activation has potential to occur at about 30%-50% of the material melting temperature[S], then a conservative yielding value of 750°F (400°C) can be approximated. An identical approximation can be made for titanium-stabilized, fully austenitic, nickel-iron-chromium alloy 825 that synonymously yields a value of 750°F (400°C). A larger factor that substantiates this high recrystallization temperature is the percent content of nickel and chromium that primarily make up these two material compositions. These factors contribute heavily to the recrystallization temperature of the material since these elements have relatively high melting temperatures; Cr, chromium melting temperature is approximately 3465°F (1907°C) and Ni, nickel melting temperature is approximately 2651°F (1455°C).

Material Creep-Rupture

Accounting for material life expectance at these temperatures involves factors such as material thickness (corrosion), maximum temperature, maximum stresses applied, and whether service is at constant temperature or at intermittently high temperature. It is important to recognize that for high temperature service, strength at temperature is related to time at temperature and with that in mind it is also important to understand that over time creep occurs. In metals, creep is a plastic deformation caused by slip occurring along the crystallographic directions in the individual crystals, together with some flow of the grain-boundary material. After complete release of load, most of the flow or elongation is nonrecoverable.[1]



Example of a Creep-Rupture Crack in a Nickel Alloy Material[5]
Bechetti, D. H., DuPont, J. N., deBarbadillo, J. J., Baker, B.A. Homogenization and Dissolution Kinetics of Fusion Welds in INCONEL® Alloy 740H, Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, accepted for publication.

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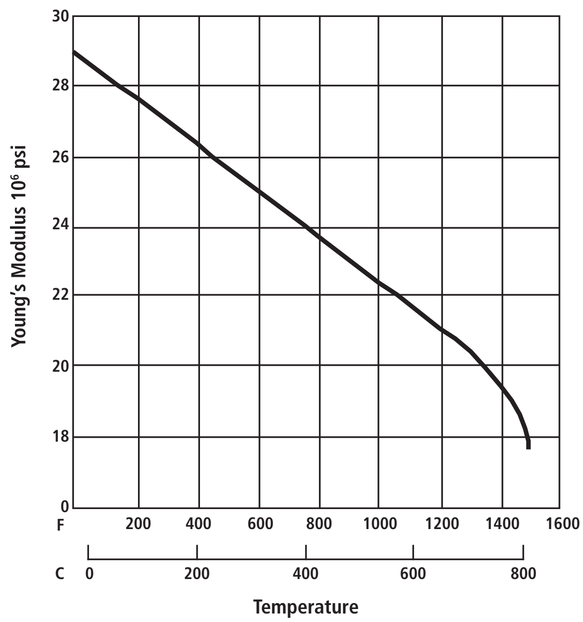
Young's Modulus of Elasticity at High Temperature

A phase transformation is where there is no change in material composition but there is one or more changes in material properties. Young's Modulus of elasticity is a fundamental property of every material property that cannot be changed however it is dependent on temperature. When temperature increases over a material, the Modulus of Elasticity will experience a decrease since it becomes easier to stretch the atomic bonds. This should be considered when designing components for downhole applications.

Figure 27
Tensile Modulus for Austenitic Stainless Steels (10)



Temperature Effect on Austenitic Stainless Steels[4]
F. Garofalo, PR. Malenock, and G.V. Smith, "Influence of Temperature on Elastic Constants of Some Commercial Steels," Symposium on Elastic Constants, ASTM STP No. 129, pp. 10 (1952)

FINAL DESIGN CONSIDERATIONS

EFL or Excess Fiber Length

EFL is the amount of excess fiber length with respect to the length of the tube (typical) that it resides in. For example, a tube that is 1,000 m long with dimensions 3.20/2.80 mm would typical utilize a nominal EFL of 0.35% which results in a accommodating fiber length of 1,003.5 m. For downhole applications, fibers are typically placed in metallic tubes comprised of 304L or 316L stainless steel. There are two notable differences between stainless steel material and optical fiber-fused silica (SiO_2).

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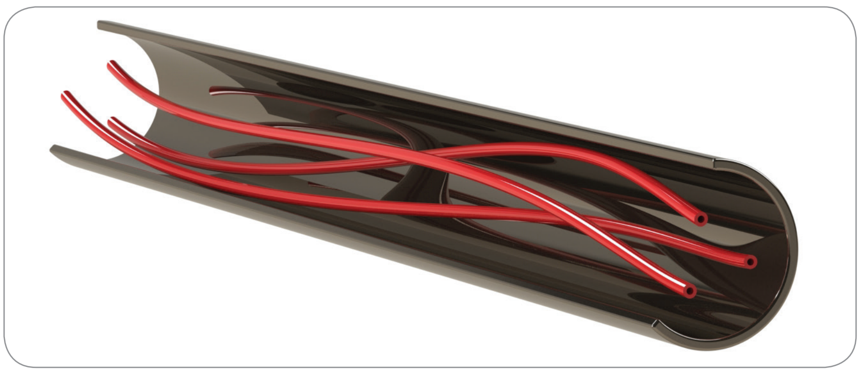
- Thermal Properties

  Linear thermal expansion is a reactionary result of temperature increase on a material. The coefficient of linear thermal expansion of Silica (SiO_2) is approximately *0.55 x 10*$^{-6}$ */°C or 0.31 x 1*$^{0-6}$ */°F* and for 316L stainless steel it averages at *18.2 x 10*$^{-6}$ */°C or 10.1 x 1*$^{0-6}$ */°F*. The percent difference between these two material properties is approximately 188.3%. In simple terms, when things start to heat up the stainless steel tube will expand radially and more so longitudinally however, the optical fiber thermal expansion is almost negligible. This thermal expansion difference is why it is important to compensate by designing in a certain amount of EFL when the stainless steel tube is manufactured. On the cold side of the temperature spectrum, having too much EFL in a tube at cold temperatures can result in coating/cladding interactions that result in micro-bend loss however, before that happens the fiber attenuation will go up due to macro-bend loss; In this case, light will escape the fiber as it is refracted through the cladding. Below is a 250 μm optical fiber of a 3.20/2.80 mm stainless steel tube.



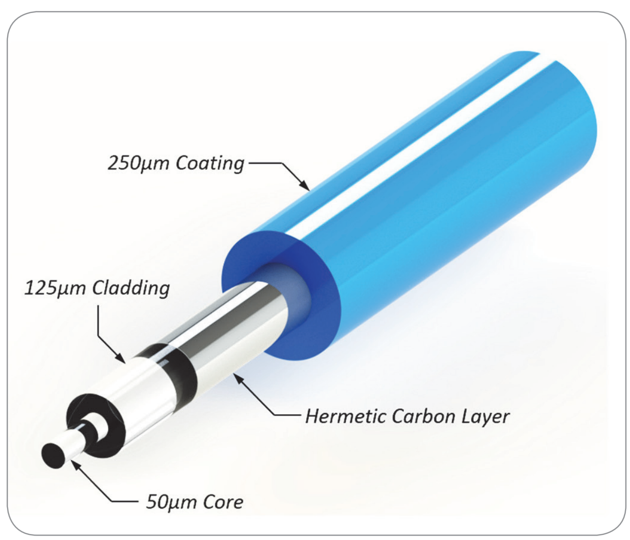
Cut-Away view of Excess Optical Fiber Length in a Stainless Steel Tube

- Young's Modulus of Elasticity

  As previously mentioned Young's Modulus, (E) is the ratio of unit stress to unit strain within the proportional limit of a material in tension or compression. When comparing modulus of optical fiber it is noted to be several times higher than that of stainless steel material. For example, if an optical fiber and a stainless steel tube were of equal length and they were both elongated by a tensile load that resulted in equal change in length, then the fiber will be under much more stress. Too much stress/strain on the optical fiber can result in power signal loss as well as attenuation thus increasing the risk of premature failure.

- Fiber Fatigue Life

  AFL Specialty Fiber offers optical fiber with an advanced hermetic carbon coating layer that resides between the optical fiber cladding and coating to increase reliability. The hermetic layer provides excellent resistance to hydrogen permeation, water diffusion, and corrosive chemical attack. Through Laboratory testing, AFL Specialty Fiber was able to verify enhanced mechanical fatigue resistance determined by both static and dynamic fatigue tests.[7, 8]



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CLOSING COMMENTS

In conclusion, it is obvious that any design must necessarily meet performance specifications, whether the design's application is in the realm of downhole completions, surface pipeline monitoring, or refinery process analysis and characterization, the majority of initial application considerations and performance requirements are driven by having assumed the temperature and mechanical loading expectations of the respective operating environment. Design reliability is a measure of the capacity of equipment or systems to operate without failure in the service environment. As a means of mitigating risk it is common to set a factor of safety at which the system must be regulated by, which in-turn increases reliability. From a system design perspective (as it relates to downhole optical cable performance), it is important to consider factors such as material selection, cable construction, and cable component interactions with respect to tensile and thermal elongation.

AFL is a leading supplier of downhole fiber optic cables used in the oil and gas industry. AFL provides the broadest portfolio of downhole products to ensure the optimal solution for each customer's specific sensing applications. With expertise in metallurgy and optical fiber, AFL provides the right fibers and associated materials to ensure success of the fiber optic cable. AFL's downhole fiber optic cables have been used in a wide variety of downhole applications ranging from steam assisted gravity drain (SAGD), where temperatures can reach 300°C, to coiled tubing (CT), to some of the deepest offshore wells.

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