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CABLES AS COMPOSITES DESIGNS AND APPLICATIONS

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SUMMARY: High Modulus Organic Fibers offered options in Electrical Cable and Tether Designs that enabled many Deep Ocean Systems and Outer Space Programs to move forward, because of their High Specific Strengths. The extension of deeper mines and taller buildings were limited by the weight of even the strongest alloy steel cables. While Kevlar®was the first such commercial fiber cable thirty years ago (Scala [1]), there are a number of other still higher strength and lower density organic filaments now in use. Ultimately their much higher Specific Strengths, coupled with being non-metallic, corrosion resistant and very flexible, has made them the optimum strength member for composite cables in advanced systems.

There are many thousands of miles of undersea fiber-optics cables with Kevlar49 (® as the strength member, so much so that the fiber is in short supply. The higher modulus Spectra has taken over the ocean tug Million pound tow rope market, while discriminating sailors chose Vectran®for yacht stays and halyards. These modern fibers are in turn the strength members in complex ElectroMechanical Cables. A variety of design and system applications are reviewed to illustrate a number of combinations of high strength fibers, resin matrices, insulations, and foams supporting the Fiber Optics and Electrical Cables and Coaxes. The very complex specifications for fatigue life, bending, tension, Impact resistance, etc, are superimposed on the Electrical and Optical Attenuation properties....all for Kilometer lengths, operating deep in Oceans or Mines, or in the vacuums of Outer Space.

Each Space Shuttle carries a number of such Advanced Fiber Cable applications, and examples will be shown of similar uses, ranging from deep in the Forests to the Aerostat, for Oil Exploration, and even Undersea Communications.

KEYWORDS : Composites, Fibers, Filaments, Cables, Ropes, High Specific Strengths, Electro-Mechanical

INTRODUCTION

The Elevator or Lift, has safely carried more passengers many millions of miles more than all other transportation systems combined, driven by cables, unseen and unheralded. G. W. Roebling manufactured his patented wire rope for successful suspension bridges, using the concept of twisted fibers that dates back in history, worldwide, for millennia. Many Systems that operate by remote control have to also transmit electric power and signals in addition to high tensile forces, carried at distances often many kilometers away, as for oil wells, or tethers in the oceans and in outer space. While a Lift Cable is a simple composite of stranded high strength wires over a core, the Under-Sea Tether can be very complex with many components, requiring both extreme flexibility and reliability. Space and Flight Cables have comparable specialties.

The following series of engineering drawings illustrate the design of composite cables for selected applications. The smaller cables such as for SideScanSonar are not illustrated, being like the centers of those shown. The methods of manufacturing and testing vary with each assembly, since all are custom designs. What they have in common are: the Synthetic Fiber strength members; the Conductors and their Insulations; the Fiber Optics Filaments (within protective sleeves and armor); and the outer protective Jacketing. Combined in stages, long lengths, formed as composites, with the common feature - Reliability.

Remote Operating Vehicles (ROV) under water **(Figure 1a)** have become a common device, carrying lights, cameras and tools. It is powered through a highly flexible Neutrally Buoyant Tether examining undersea wrecks, oil rigs, sewers, helping divers. Its half inch diameter tether tracks along with minimal interference to the maneuvering vehicle that operates from an under-water carrier, the garage, which in turn can be either a submersible vehicle, or a cable to the surface ship. **Figure 1** illustrates the design for a much larger tether to an

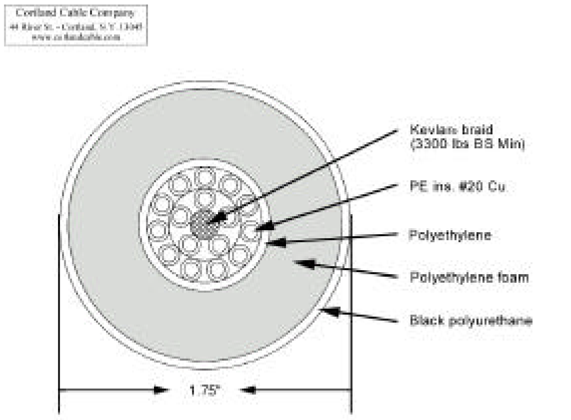

Figure 1 Neutrally Buoyant Power Cable

1.75" diameter 3300 lbs. Break strength One km length

undersea tractor, with the same elements of a core strength member, layers of insulated copper conductors, a foam and outer jacket. For flexibility, these have very fine wire twisted copper strands with extruded high voltage insulation. Beside high voltage spark testing, each wire is water pressure tested before assembly. A counter spiraling and cabling improves flexibility; and a low shear water-blocking matrix seals the Poly-Ethylene inner jacket. The foam for neutral cable buoyancy depends on the operating depth, protected with the tough Urethane outer jacket. Each of the resin components has its own specifications and test requirements. In addition to the insulation testing, any coax wires and fiber optics have to meet impedance and attenuation specifications. While the strength member is minimal, recovery problems can call for high retrieval rates and maneuvers, with a minimum of cable memory or resistance, and without buckling or kinking. Many commercial ROVs are much smaller systems, built for long distance maneuvering in complex pipe water and sewer systems, operating where divers cannot go.

There are now large underwater trenching machines, much like great plows on tracks, that have to operate through these tethers, calling for both electric power and instrument controls. These are made to carve their way even through rock and sand, burying the cables as much as ten feet, and covering up as they move along. All of the cables that come ashore, have to be so protected, and the controlling tethers come from the offshore ships or stations. The unit in Figure 1a is but one of many designs, and most all custom made to operate different tools, for oil and gas lines or undersea exploration.

Figure 1a – Undersea Maintenance ROV

The **Hydrophone** is a sensor used to identify a source or message by the sound or pressure changes, arriving through the air or water. The geologist uses this device for identifying the strata most likely to produce oil. By trailing cables behind a cruising ship, as shown in **Figure 2a**, and setting off periodic explosions or electrical discharges, the sensors in the array of cables can pick up the reflections from the ocean bottom. With a prior knowledge of the character of these reflections, the geological survey can very efficiently explore vast areas.

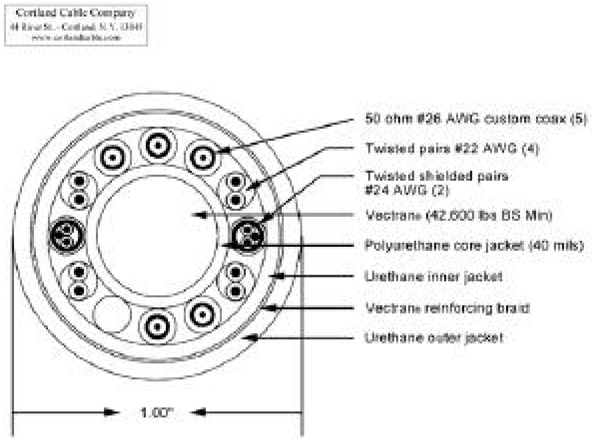

Figure 2 Hydrophone Vertical Array

1.00" diameter 25,000 lbs. Break strength One km length

The cables have to be made to survive the deployment, with the hydrophones attached anywhere along their length. One could simply attach the instrument at the end of the cable that contains the proper conductors, which unit also measures temperatures and the water properties. In order to get maximum use of the cable, the instruments are buried at fixed points along the cable length. The cable must therefore have the strength to trail along at high speeds (10-20 knots), with minimum size and drag, at a controlled level in the sea, and have its wires accessible at all points along the length, to mount the instruments.

Figure 2 is a cross section of a typical Hydrophone cable that has a high strength core, in this case using a cabled Vectran of over 42,000 lb BS, with a variety of conductors cabled over the Urethane Core Jacket. The conductors include twisted pairs for instrument power, shielded pairs, and co-axials. These are all custom made and pressure tested, and the wires identified so that they can be connected electrically and then encapsulated or potted to the instrument sections. All this by surgically opening the outer Urethane jackets, at specific distances, and then potting or closing for a perfectly sealed Hydrophone.

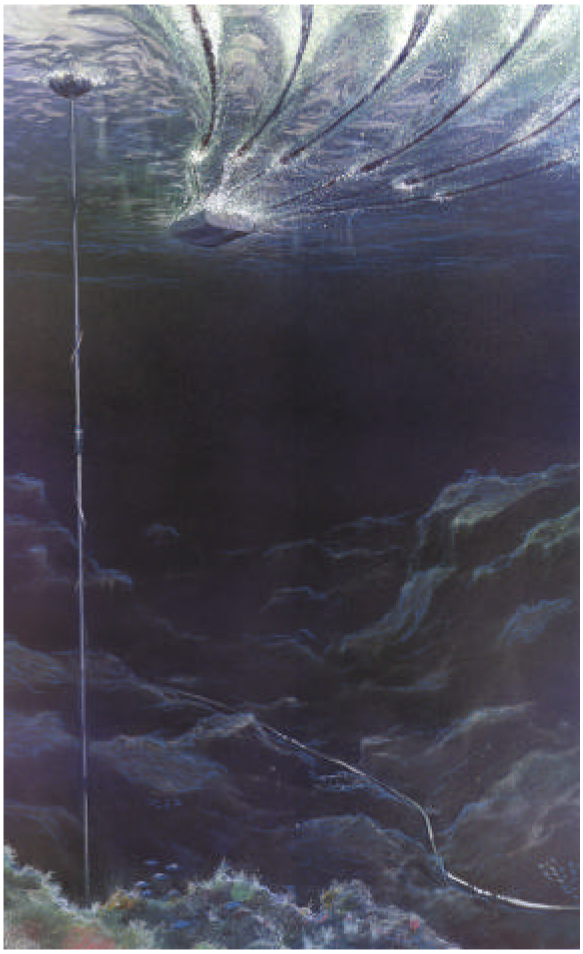

Figure 2a – Hydrophone Cables: Towed, Vertical, and Seabed

These wires, shielding, insulations, etc. are built in sequentially, working with Kilometer lengths, with either Cortland or the Customer installing the hydrophones later. An added feature is the Hair Fairing applied over the jackets, to break up the vortexes that track behind the towed array, and prevent excessive aeolian-type vibrations. These Hydrophone cables are brought aboard periodically with giant winches, and deployed from the decks, underway at times in severe sea states, requiring very rugged designs and materials.

The Hydrophone Cable drawing is for a Vertical Array, carrying many hydrophones, or it could be designed for a sea bed location, as shown in the lower part of Figure 2a to pick up and identify sounds generated at sea. They often have to withstand very high tensile loads, during towing, deployment or recovery requiring high tensile strength cores. When the array has to fall away rapidly from the ship, then the steel cable weight is an asset, but an increasing number of systems call for the high strength synthetics. When very long lengths or depths are involved, the power for winching becomes prohibitive, particularly for the high speeds needed to retrieve in a reasonable time span.

Cortland has almost no off-the-shelf cables. Each system is custom designed and built, with cable lengths ranging from a few hundred meters for sampling cables to 10,000 meters for deep well logging cable. Conventional oil well logging cables or Transoceanic Fiber Optics Cable are made by world-class corporations. The Specialty Cable Systems call frequently for very high voltages or currents, and sophisticated dielectrics for digital signal sizes range from a few millimeters in diameter and kilometer lengths, to complex mixes of electrical and optics, no two alike. Most often the coaxial conductors are alongside current or signal wires, and Fiber Optics. Provisions must be made in the cable design and manufacture, to prevent either mechanical or electrical distortions.

The King of the Cable Composites is the TransOceanic FiberOptics, linking every continent and island around the world, a conference subject in itself. They are buried for protection near anchorages and shelves near shore, and the Giant Crawlers that plow in and cover these cables are also operated by tethers. But crossing the oceans, the cables hang down as catenaries, most often to great depths over 7,000 meters, laid by some of the largest ships in the world, carrying many continuous miles in their holds. A decade ago, these Trans-Atlantic cables were complex electrical coaxes with periodic repeaters every so many miles. Today they are the more efficient Fiber Optics. The cables discussed here are their smaller cousins, but complex composites with highly specialized requirements and frequently no two alike as the system requirements improve. Both the commercial and the military requirements quite often have similar components. The complexity and the variety of conditions make these unique and unheralded composites. Operating undersea or outer space requires maximum reliability. A cable failure can mean not just the loss of instruments, but the weeks wasted by crews and equipment.

The **Helicopter Cable** cross-section in **Figure 3** is for a Logging Operation, with a 30,000 lb Break Strength core of Vectran®, a new Celanese synthetic fiber that has both higher fiber strength and abrasion resistance. The braid construction, similar to a plait rope, results in a more flexible cable, since loggers are accustomed to the very tough steel cables, often just wrapping the cables over the logs. This also applies to the use of the braided outer polyester jacket, instead of an extruded urethane. The conductors are to operate the automatic

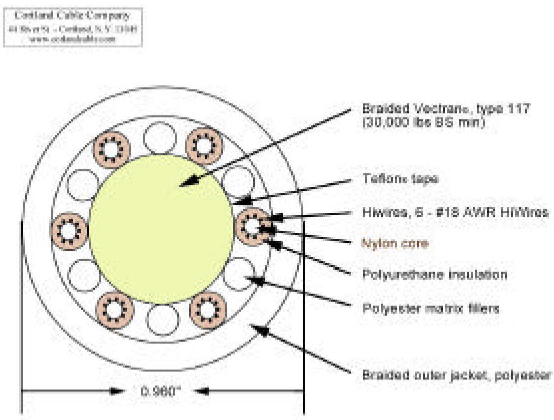

Figure 3 **Helicopter Cable**

0.960" diameter 30,000 lbs. Break strength One km length hook release mechanisms. These are the special High Impact Wires (HiWire®), used in glider tow ropes and rocket fired explosives ropes. By spiral wrapping the fine wire conductors over a nylon core, beneath the extruded insulation, the conductors can recover after elongation, without the classic z-kink failure. This design was also used in the NASA/Agencia Spaziale Italiana, a 20 km Space Tether. The conductors and fillers are cabled over the core with an elastomer matrix, under heavy or heavy fabric jackets.

The **Figure 3a** shows a standard practice of rescuing or transporting heavy equipment from a Heavy-Lift Sikorsky Helicopter. This uses large Spectra Slings made in a grommet design. Such slings are used in conjunction with splices, hooks, shackles, spreader bars, and many varieties of attachments, depending on the application to trucks or tanks, etc. Weight of the hardware is the key factor because the personnel must climb about the loads attaching the fittings, under the hovering giant helicopter. Some of the lift systems have electrically controlled hooks, and these attachments with steel ropes and fittings, are massive. The Spectra Tethers have replaced the heavier systems.

There are also cables down to 1/4" diameter for the common rescue hoist systems for helicopters, replacing stainless wire rope, attached to baskets or harnesses. The static charges that can be built up by the helicopter blades, transmitted by these cables, can at times cause serious problems, and the procedure for discharging by prior grounding can be dangerous. Newer hoist systems use special Kevlar cables, but must be used on the same winches. Matching the strengths, toughness and residual properties of the steel has been done, but the acceptance has been slow.

Figure 3a – Helicopter Rescue and Transport

As for all engineering systems, replacing steel that works, with synthetic fibers, is not popular. Tower antennae guys have always been steel, for example, and even where corrosion destroys the steel, tradition and perceived ‘strength’, make the acceptance of the new fibers very slow, in spite of far lower installation costs. For shipboard applications, the guys, life lines, and rigging have seen more composite synthetic fiber lines replacing steel, with the major criteria often being the mode and ease of assembly, and the lower cost of the steel. But stainless is more expensive than most synthetics, and the penalty of higher labor costs for installation can be a major factor. If the cost of the electrical winching systems are factored in, space, power and size, then the penalty of the heavier steel systems can be severe.

Large Kevlar or Vectran Tethers are used to fly **Aerostats**, aerodynamic-ally shaped helium filled balloons - high altitude blimps that are without engines or internal frames. **Figure 4a** is a Type 420 in flight, just released from its mooring tower with its control Tether, on the way to its cruising altitude of 4,500 meters. The 64 meter long by 21 meter diameter Aerostat supports a pod containing the 8x5 Meter L-Band Radar Unit. They are deployed to monitor air and sea traffic out to 200 nautical miles, along the East, West and Gulf coasts of the United States. Countries with flat Terrains, like Saudi Arabia and Fiji also use these vehicles as antennas to transmit by radio, maintaining communications, weather reports, traffic control, etc. The designs and controls vary with each station, but typically a 6,000 Meter Tether is on a reel that rides on a 1 km radius circular track, to control the vehicle as it shifts with the wind. They can operate through storms, but in typhoons they are hangered.

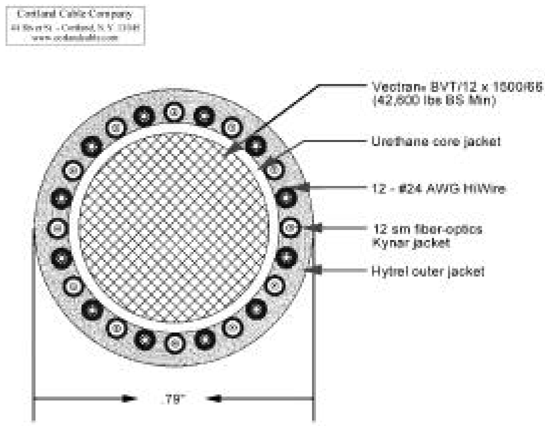

Figure 4 **Aerostat Cable**

.79" diameter 42,600 lbs. Break strength One km length

The cross section of one such Aerostat Tether is shown in **Figure 4** with a 42,000 lb BS Vectran braided core, within a Urethane extruded jacket. A Braid construction insures a Torque-balanced Tether. There are both HiWire designed Power lines, and Fiber Optics also Cabled around the Core, contained within a polyester fabric jacket that also supports and locks the elements in place. The cables are terminated with bridles, splitting the conductors and F0s from the mechanical core that goes directly to the Tendons or strength members that give and retain the inflated shapes.

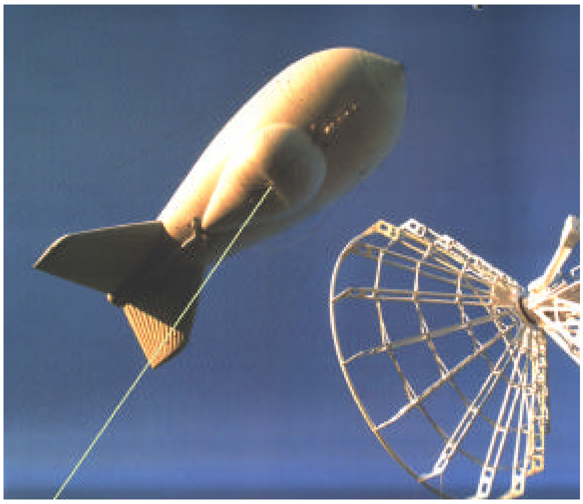

Figure 4a – A 420K Aerostat being launched.

In some large Aerostats, there are also electric motors requiring larger high voltage power inputs. These Tethers have very heavy three-strand copper cores akin to welding cables, with high voltage insulations. An outer Kevlar 49 counter-helix construction is used to build up the Torque Balanced strength member, permitting high strengths over 50,000 lb. The upper tether section is reenforced to compensate for the severe flexing and loading when the vehicle is brought in and stored close to its mooring mast.

The **Water Sampling Cable** illustrated in the **Figure 5** is an example of a hollow tubular core, with the strength member just under the outer protective urethane jacket. In this instance the tube carries water from the conduit, river, or body of water being checked for contaminants. It is either a nylon tube, or a special surgical rubber, in the case of cables carrying air, such as for divers, since this type of design can apply to any fluid transfer cable. The cable has to be designed and operated to avoid kinking, usually by maintaining the higher internal pressure.

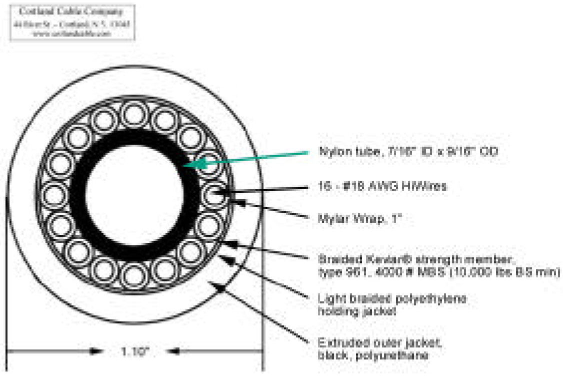

Figure 5 **Water Sampling Cable**
1.10" diameter 10,000 lbs. Break strength One km length

Again, it is HiWire®that is used for the conductors, both for power and for instruments, the insulated wires being spiraled over the tubing to maximize flexibility. In this design, the outer conductors are Mylar wrapped to keep them locked in place, plus a braided Kevlar strength member of 10,000 lb., protected by a braided polyethylene. The final outer extruded urethane jacket has to resist severe abrasion against pipe and stone walls, yet remain flexible. The tensile load is always taken by the low elongation/high modulus Kevlar. Note that these internal composite elements have to slide by one another in bending, much like a deck of cards, and recover in place, withstand extensive cyclic loading, and be deployed from reels. Elastic non-hardening filler is used to water block the cables, and prevent local leaks from destroying a cable, and also acting as an internal lubricant. . High interface shear loads and bonds would result in buckling and self destruction, whereas the high shear strength is needed in conventional fiber reenforced composites or laminates.

Figures 6 and 7 illustrate the degree of complexity in **large Umbilical and Array cables**. Cables with hundreds of conductors and Fiber Optic elements are common enough in communication systems, buildings, ships, etc. They are, however, simply fed into conduits or trays, supposedly protecting them from vibrations and contaminants. Witness the disasters that occur in aircraft, when trays of conductors are accidentally exposed to leaks from a galley or lavatory. The smaller wire harnesses save weight and space, and they would become much more complicated if made by the cable standards discussed here for marine and space applications. Future safety requirements may well force the adoption of the better designs and materials available for dynamic systems. Realizing that an airplane or ship is actually a ‘flying’ computer, the ultimate safety would be greatly improved, preventing electric failures from abrasion, impact, or shorting between wires. Fires and system failures in commercial systems would be much less frequent with the designs and materials shown above.

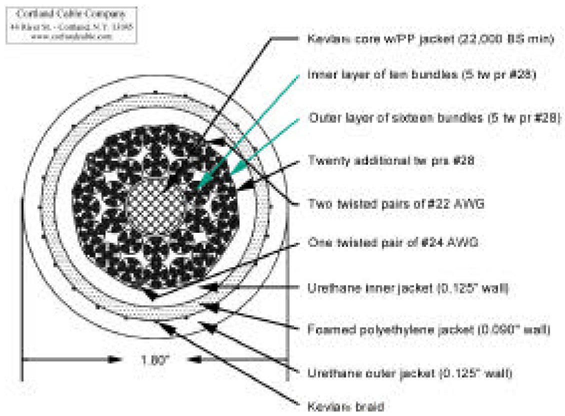

Figure 6 **144 Channel Array Cable**
1.80" diameter 22,000 lbs. Break strength One km length

The 144 Channel Array cable in Figure 6 does not require much mechanical strength, but the combination of the Kevlar Core (22,000 lb BS) and the outer Kevlar jacket can cope with any deployment loads, as well as providing protection for the hundreds of wires that have every conceivable combination of shielding, insulation, capacitance, etc. They do not happen to have any Fiber Optics, but most often designers have the FO added for future use.

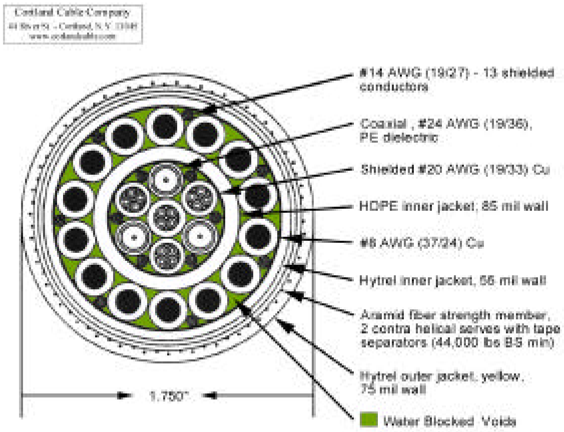

Figure 7 Undersea Umbilical Cable

1.75" diameter 44,000 lbs. Break strength One km length

The Undersea Umbilical Cable is for the operation at great depths, for track driven trenching machines, laying large cables over not only hundreds of miles of ocean bottom, but plowing ten foot trenches through Coral and rocks as the shores are approached. On land the larger cables are also buried, and even overhead wires on ancient telephone poles are being replaced by underground wiring, so that tunneling equipment and underground cables are taking over in urban areas. **Figure 7** would represent the type of cable between cities or between complex machines with coaxial lines at the center for sensitive signal and data systems, while the exterior conductors carry high voltage power. The 44,000 lb BS Kevlar outer braid serves both to armor the cable to and handle the extremes of tensile loads in deployment or installation. Again the Water Blocking is the flexible filler that prevents and limits the incursion of water.

While the cross section drawing of a cable defines the design and components, the portrait of a full cable is difficult. **The Collection of Cables** in **Figure 8** shows the range from a single FO 2mm (1) to the 45mm Under-sea Umbilical (2). The orange-jacketed upper cable is the ROV Tether. The Tow Cable (3) with its vortex shedding Hair-Fairing and the Water Sampling Cable (4) show the diversity of designs that can be supplied at kilometer lengths.

Figure 8 – Collection of Cable Sections, Including the Hair-Fairing and the Buoyant.

CONCLUSION

The combination of materials and operations that have to be used to design and produce cables are more complex than composites used just as rigid structures. The major factor is the need for great flexibility since most are deployed under very dynamic conditions. Fatigue failures, wear, cyclic loading problems etc. are superimposed on tensile and bending loads, and quite often, severe torque and impact loading. The combination of electrical, thermal, and mechanical requirements are superimposed on extremes of water pressure, corrosion, or vacuums. The development of very high strength and modulus organic fibers has meant that cables could be designed with much higher corrosion resistance, and lower weights. While their costs are higher than steel, they are usually less expensive than the high alloy steels needed to prevent oxidation or corrosion are involved. The use of these modern fibers for flexible systems mitigate against the use of high shear bonding to a matrix. The matrices that are used usually have to usually remain flexible. This also relates to shelf life, which for most of these organic fibers has been incredibly good. These high modulus fibers have retained their properties for ten years and more, but not if exposed to ultraviolet light. Similarly, they will not stand up in outer space exposed to the high energy particles and monatomic gases, as is true for all organic materials exposed to outer space. All the parameter studies show the superiority of these low density advanced filaments, whether for conventional composites or in systems requiring cables. The electro-mechanical cables most definitely require the best of composites technology, and call for an advancement of sophisticated analytical methods like Finite Element Theory, to be applied to flexible strictures. The structural design of an undersea creature, like a shark or porpoise, is still not well enough understood. They are natural examples of dynamic and flexible structures. Their composites of fibers and tissues in the skin, cartilage, sensors and muscle far excel what we can design or build - that can both heal and reproduce. The undersea cables in fact, simulate the basic elements of these vertebrates.

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