Cable in Search of *Endurance*

Fiber-Optic Design for Expedition of Shackleton's Legendary Wreck

By Stephen O'Riorden

Whether to use an AUV or ROV, that was the question. Each has its distinct advantages, but this was a rather unique shipwreck. This was the famous Sir Ernest Shackleton's *Endurance*.

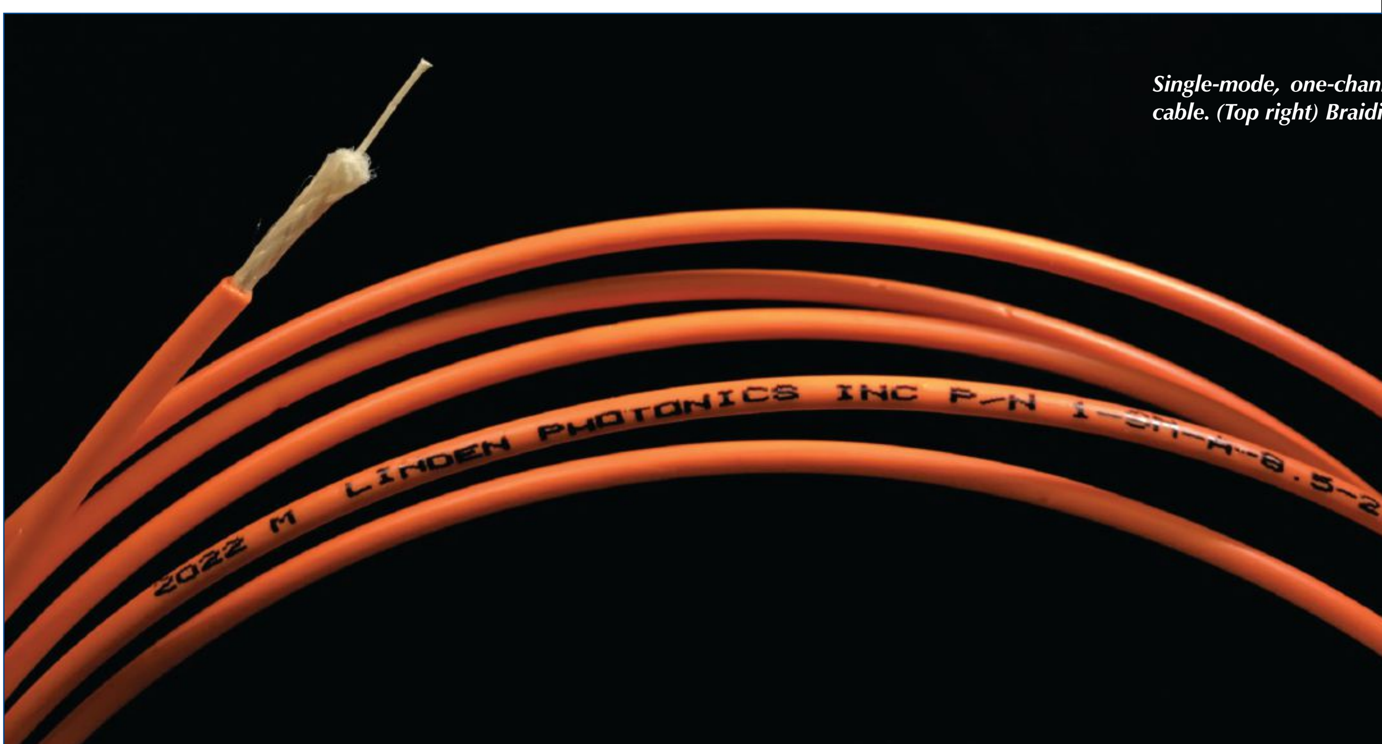
On the Imperial Trans-Antarctic expedition of 1914 to 1917, the *Endurance* became stuck in pack ice, and after nearly a year at its mercy, *Endurance* slipped below the surface. This story captured the fascination of the world due to its tales of extreme survivalism and miraculous rescue of all 22 men, who survived polar conditions for over 18 months. Flowing ice and unknown currents made the exact resting place a mystery for over 100 years.

AUV vs. ROV

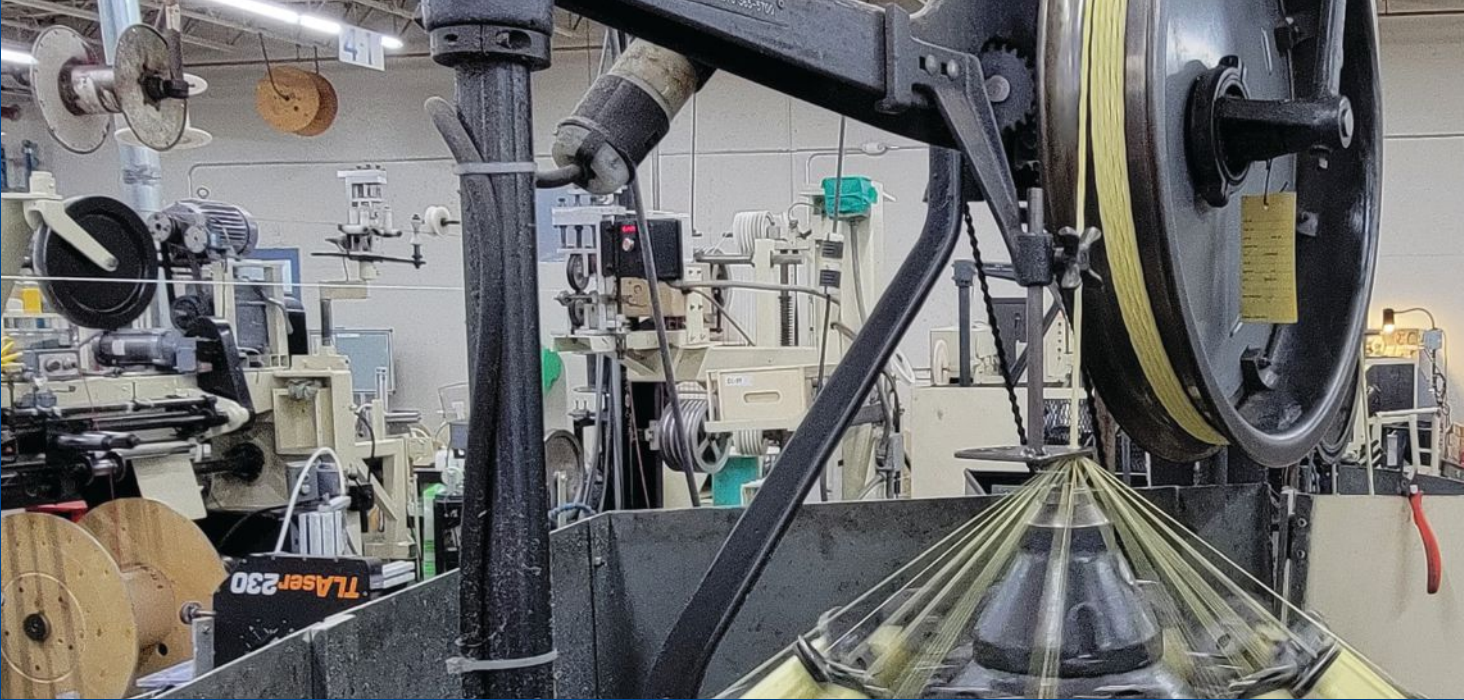
In March 2022, the Falklands Maritime Heritage Trust announced that *Endurance* had been found 4 mi. south of its last recorded location.

Searching for a shipwreck in the vastness of an ocean is one thing, but searching for one 3 km beneath the thick Antarctic Ice Shelf is another thing altogether, presenting unique challenges and dangers.

In an open-sea situation, one may be able to employ an AUV, sending it on its mission and awaiting to retrieve valuable data upon return. In this case, however, the polar environment is too unpredictable to bank on the safe

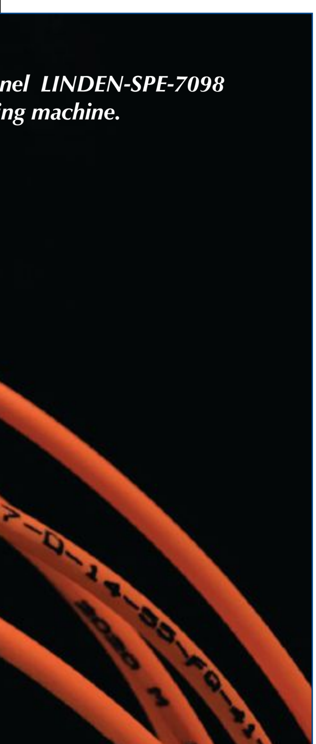


Single-mode, one-chan
cable. (Top right) Braidi



return of an autonomous vehicle. Use of an AUV is an all-or-nothing proposition. Since underwater high-bandwidth wireless communication can only work up to 50 m, the vehicle must return to the ship to transmit data. This was a $10 million mission, and the inability to retrieve any data should the AUV be lost under the ice was a risk the team was not willing to take.

Using an ROV in this situation would present its own difficulties, as the team would need to decide on the type of ROV, appropriate cable design and tether management. Ultimately, a battery-powered ROV (Saab Sabertooth) was chosen, which allowed for the use of a fiber-optic tether solely for communication.



nel LINDEN-SPE-7098
ing machine.

Cable Design

Linden Photonics was brought on to design the cable. Given that the exact location of the wreck was unknown and at 3-km depth, the communication link to the ship would need to be quite long. Practically, the extreme length of the tether would rule out an electro-optic cable. Transmitting power over long lengths would require conductors of such large size that this type of cable would be unmanageable.

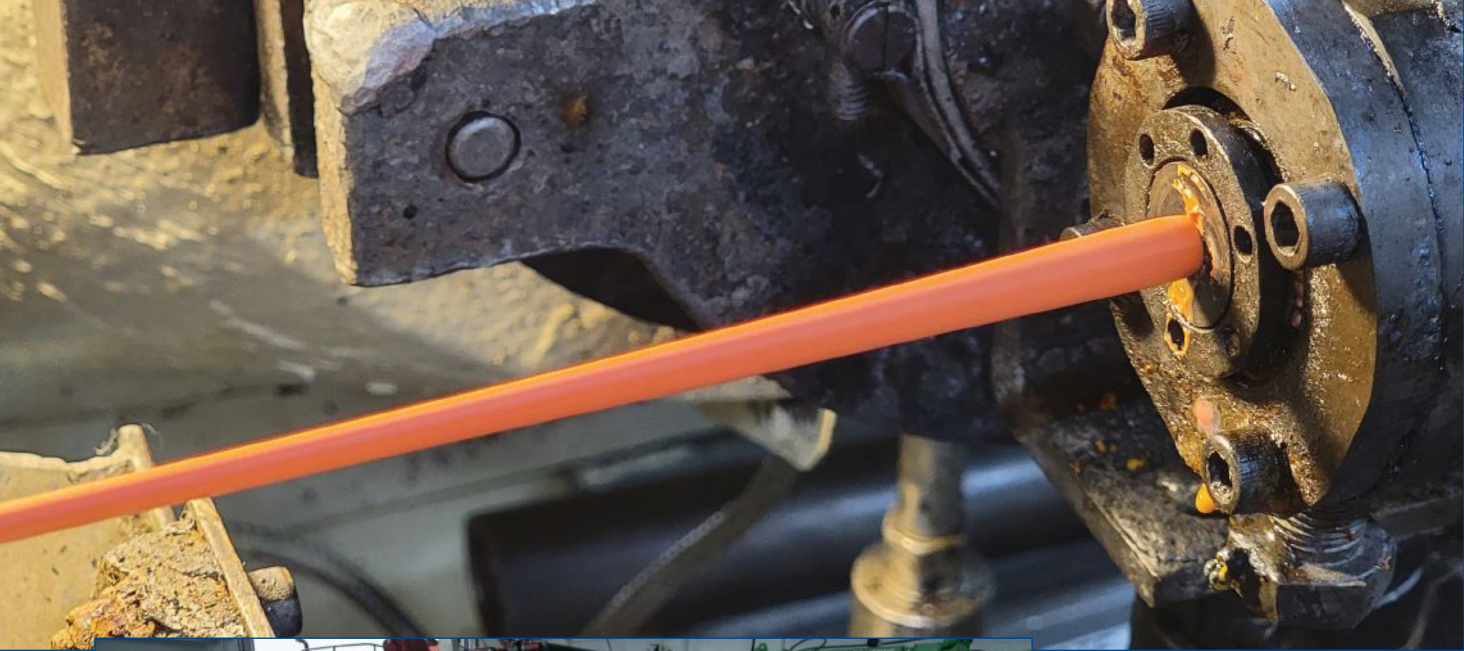
The cable chosen for this expedition was the LINDEN-SPE-7098. Linden Photonics had already been outfitting Sabertooth ROVs with a fiber-optic tether of significant lengths (more than 3 km continuous). This cable is a high-strength, low-profile, neutrally buoyant design. At 3.5 mm in diameter, it has a tensile strength of more than 350 kg, and its density nearly matches that of seawater. The basic building block of the cable lies in the STFOC (Strong Tether Fiber Optic Cable) at its center. This patented technology relies on a jacket of extruded LCP (liquid crystal polymer) designed to provide strength and moisture protection to an otherwise delicate, bare fiber-optic element. Surrounding this center fiber-optic element are torque-balanced Vectran strength members. Vectran yarn is made from the same resins as Linden's LCP strength members and exhibits an ultimate tensile strength of approximately 450 kpsi when made into fibers about 23 µm in diameter, due to the high level of molecular alignment. The cable was finished with a ruggedized, low-density polymer outer jacket.

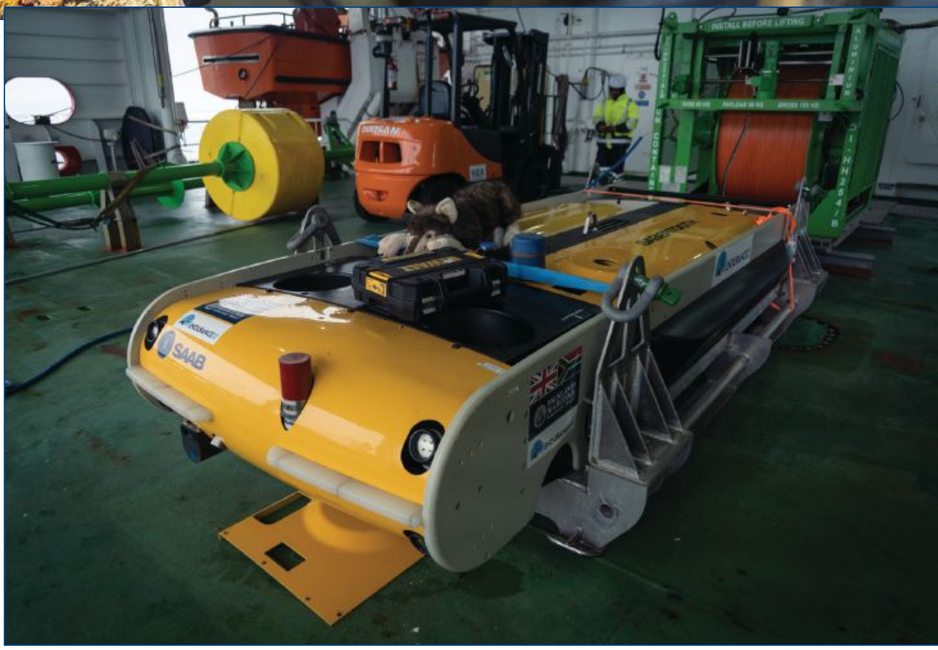
Manufacturing Challenges

As with any type of manufacturing, cable manufacturing presents unique challenges. Cable yield is an issue for every cable maker. A single glitch during manufacturing can often lead to irreparable defects in the cable. If such a defect occurs in the middle of a 1-km run, the result is two cables 500 m in length. Joining these two fiber-optic cables is really only possible through use of a fiber-optic connector—and the use of a fiber-optic connector will ultimately lead to an increase in diameter at that location, optical insertion loss at the connection point and usually a significant loss in tensile strength. Additionally, even the most low-profile connector will present issues with cable winding.

Because of all this, Linden Photonics was tasked with building a single continuous length of cable, something we are very acquainted with doing regularly. Particularly with our STFOC cables, we can routinely produce single continuous lengths close to 50 km. However, for the LINDEN-SPE-7098, the braided strength members and outer jacket present other yield issues.

Extruding the primary and secondary layers of STFOC onto bare fiber is done at a high rate of speed, such that each layer of a 50-km length can be manufactured in a





(Top) Extrusion of low-density outer jacket. (Bottom) LINDEN-SPE-7098 attached to Saab Sabertooth ROV. (Credit: Falklands Maritime Heritage Trust)

single work shift of less than 8 hr. While this can also present yield issues, we have developed a robust process and can routinely produce such lengths.

Applying strength members over the STFOC is a different story entirely. Braiding is a mature process that has existed for a long time. Ropes, for instance, are widely available in many shapes and sizes, but generally only offered in short lengths, with a maximum length generally a few hundred meters. Braiding 25,000 m of strength members over the STFOC is a long-term project that requires constant attention and management.

While the STFOC is a tough fiber-optic element, the 16 individual strands of Vectran designed to provide more than 350 kg break strength are stronger. A 16-carrier braider intertwines 16 individual bobbins of Vectran around the substrate, and proper tension must be kept on the fiber-optic element as it is braided to avoid kinking and sharp bending that could result in a discrete loss point or, at worst, an optical break rendering the cable useless.

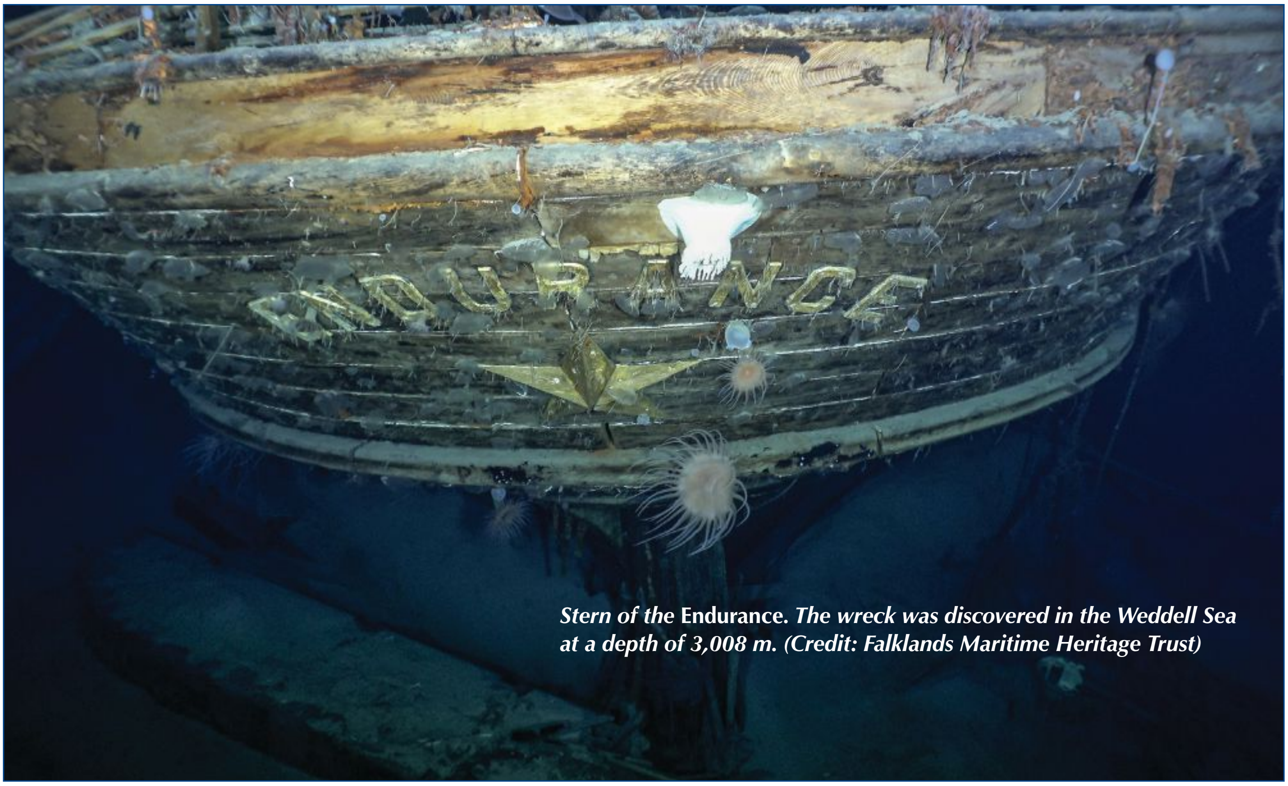
Braiding of the strength members is the slowest part of the process and the one with the most chances for failure. Due to the fact that the production rate is on the order of 30 to 45 cm/min., even running a two-shift operation, this part of the process will still take nearly 12 weeks for the full 25-km length.

Additionally, the bobbins can only contain several hundred meters of material and will need to be continually replaced during the process. This insertion of new material is called a tie-in. These tie-ins are staggered along the cable so that they don't all occur in a single location. At a single location, the resultant increase in overall diameter at that location would be problematic for smooth extrusion of the outer layer.

Tending to this process for 12 straight weeks; maintaining proper tension; replacing bobbins of Vectran and manually tying them into the braid; checking for material buildups at any of the guiding grommets; and various other necessary manufacturing controls make for a tedious process critical to the final outcome.

Extrusion of Outer Jacket

The principles of extrusion for the outer jacket are



Stern of the **Endurance.** *The wreck was discovered in the Weddell Sea at a depth of 3,008 m. (Credit: Falklands Maritime Heritage Trust)*

much the same as for that of the STFOC jacketing. First, the resin is fed into the hopper. This holds the resin and feeds into the barrel. The barrel and screw are heated to appropriate temperatures to soften and melt the resin in stages. As resin moves from the hopper into the barrel, it is pushed toward the cross head by a screw. The screw design is critical and must be matched to the resin one is extruding.

The screw moves the melt forward, which then goes into the crosshead and turns 90°. The substrate, in our case, a 25-km-long, braided fiber-optic element, to be coated is fed from the back through the center hole of the mandrel. The fiber and melt are now moving in the same direction within the crosshead. Finally, the fiber and melt exit from the front face of the die where the melt contacts the fiber. If all parameters are set correctly, the melt forms a jacket of a controlled thickness and uniformity around the fiber. The coated fiber is immediately immersed in a water trough with running water to cool and solidify the melt rapidly.

This process is not without risks. Even though this is run at a much higher speed than braiding (approximately 25 m/min.), it still takes 16 hr. to complete. And unlike braiding, the process cannot be stopped and restarted. If for some reason the process breaks down at any time during the 16 hr., the result will be a cable that is not 25 km in length. Because of this, one must continually monitor the process, looking for any issues.

A decrease in material output, changes in tension in the payoff or take-up spools, die drool, etc. all have to be attended to by a competent and knowledgeable operator for the full 16 hr. For such a long run, even situations that are beyond our control must be considered, such as power outages. Because of this, the possibility of storms in the area must be taken into account, and the timing of such a long run needs to be scheduled on a day with no weather events forecast.

The Final Result

Assuming each and every step in this process goes without incident, the result is a continuous 25-km-long, fiber-optic cable. Nevertheless, there is one final check of the optics that must be performed in hopes that nowhere along the line is the delicate underlying fiber-optic glass adversely impacted. This is performed with an optical time domain reflectometer, which transmits light pulses along the entire length of fiber and allows an operator to look at the full cable from an optical perspective.

For the *Endurance* mission, Linden Photonics performed this process not once but three times—successfully.

On March 5, 2022 with the 25-km cable attached to a Saab Sabertooth ROV, after days of running patterns on the seafloor beneath the Antarctic ice, the *Endurance* was located. This was the first time anyone had laid eyes on it since it sank beneath the sea over a century ago.

Sir Shackleton himself surely couldn't have imagined that the next time anyone took a look at his fateful ship it would be via an underwater robot with digital images transmitted by light pulses along a 9-μm-wide, 25-km-long glass conduit. Perhaps even the great polar explorer would be impressed. **ST**

Stephen O'Riorden is the president of Linden Photonics Inc.