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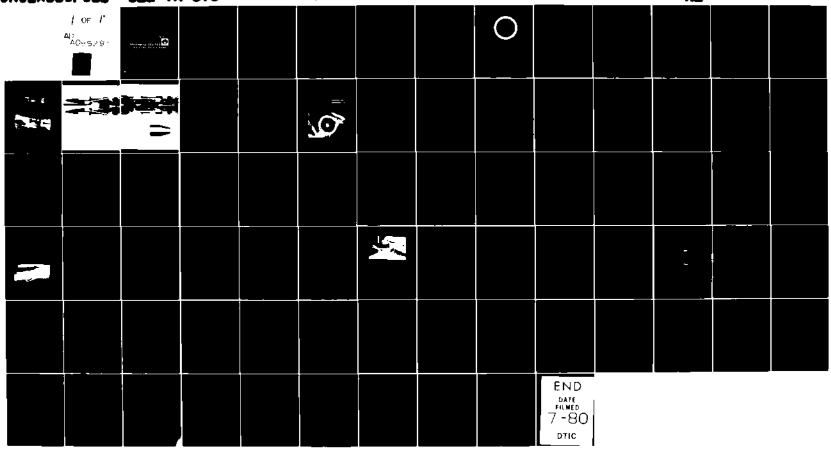

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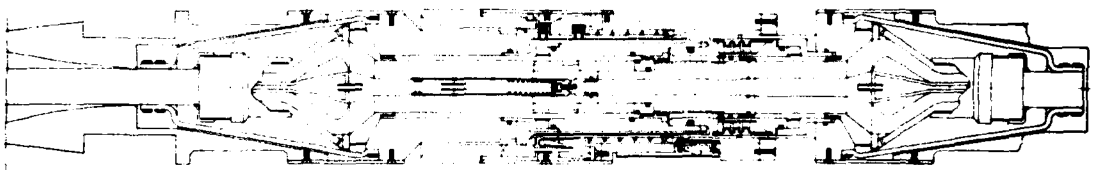

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TECHNICAL REPORT

CIVIL ENGINEERING LABORATORY

Naval Construction Battalion Center, Port Hueneme, California 93043

COAXIAL UNDERWATER MATEABLE CONNECTORS –
A New Technology for Seafloor Structure Applications

by

J. V. Wilson

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As part of the Deep Ocean Technology Program, an underwater-mateable coaxial connector for SD list 1 cable has been developed ~~at the Civil Engineering Laboratory (CEL)~~. The CEL-3 series connector includes the following features: oil-filled, pressure compensated, coaxial throughout, full cable breaking strength, both manipulator and diver compatibility, unlimited depth operability, and estimated 10- to 20-year life. Four complete units and next page

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several subsystem mockups have been built and thoroughly laboratory-tested. Limited field tests and at-sea demonstrations have also been conducted, culminating in a 2-year, 6,000-foot demonstration of the CEL-3B prototype. After minor modifications and debugging, the prototype CEL-3B met all performance requirements, including impedance matching to within 2%, 6,000-volt DC operation, pressure testing and wet mating to 5,500 psig, mating by submersible, unmating under 10,000 pounds of tension, and sustained submergence without degradation. The variety of designs tested provides a basis for extending the CEL-3 series concept to a wide range of applications – from deep ocean cable repair to modular assembly of advanced ocean cable structures.

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As part of the Deep Ocean Technology Program, an underwater-mateable coaxial connector for SD list 1 cable has been developed at the Civil Engineering Laboratory (CEL). The CEL-3 series connector includes the following features: oil-filled, pressure compensated, coaxial throughout, full cable breaking strength, both manipulator and diver compatibility, unlimited depth operability, and estimated 10- to 20-year life. Four complete units and several subsystem mockups have been built and thoroughly laboratory-tested. Limited field tests and at-sea demonstrations have also been conducted, culminating in a 2-year, 6,000-foot demonstration of the CEL-3B prototype. After minor modifications and debugging, the prototype CEL-3B met all performance requirements, including impedance matching to within 2%, 6,000-volt DC operation, pressure testing and wet mating to 5,500 psig, mating by submersible, unmating under 10,000 pounds of tension, and sustained submergence without degradation. The variety of designs tested provides a basis for extending the CEL-3 series concept to a wide range of applications – from deep ocean cable repair to modular assembly of advanced ocean cable structures.

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INTRODUCTION

Coaxial cable is presently the most effective means of transmitting electrical signals over great distances underwater. Such cable is also capable of carrying significant amounts of electrical power on the same conductors. In various forms it is used as the trunk line for major military seafloor installations as well as for commercial telecommunications networks. Coaxial cables also are the heart of several developmental systems for acoustic research, deep ocean work systems, and seafloor installations.

Cable connectors in general can add great flexibility in design, installation, operation, and maintenance of various systems. Underwater-mateable (wet) connectors can increase ocean system effectiveness even further; but to keep the low-loss, low-noise properties of coaxial systems intact, the connectors must also be coaxial and must be impedance-matched.

To provide the technology necessary to make wet coaxial connectors a viable option for system design, CEL, under the sponsorship of the Deep Ocean Technology Program administered by the Naval Facilities Engineering Command, began the development of a coaxial wet connector in July 1974. SD cable (described in Reference 1 and shown in Figure 1) was chosen as the host cable system because it is an important existing cable and combines most of the difficult cable features that may be encountered in designing a wet connector: stringent coaxial construction tolerances; high voltage transmission of DC power (corona noise); polyethylene dielectric (poor bonding flexibility); center strength member (difficult to terminate); and bulky, stiff cable construction (difficult to handle during connector mating). Development of this connector provides a firm base for extension of technology to future connector/cable design problems.

Early efforts in wet connector development (Ref 2) had shown that high-voltage systems could be successfully mated underwater, and this work provided the technical design approach for the coaxial work. During the coaxial program, four connector models were built and tested. A wide variety of connector features were investigated, and considerable insight was gained into just what will and will not work in underwater cable applications. This report summarizes the development of the coaxial connector; provides design guidelines for extension of the design to production model SD connectors, smaller coaxial connectors, and other items; and also covers some of the useful test methods and techniques developed in the program.

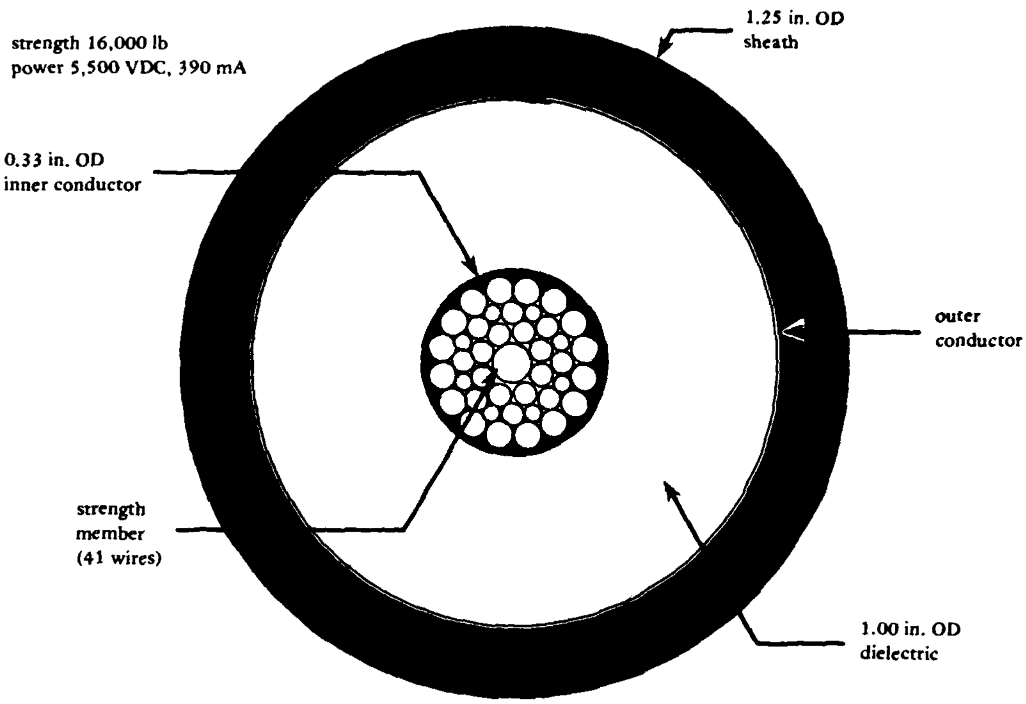

Figure 1. End view of SD list 1 cable.

In addition, a discussion of the applicability of these coaxial wet connectors to ocean facilities and other systems is provided. A discussion of the history, state-of-the-art, and general design principles of wet connectors for various other applications is included as Appendix A.

PERFORMANCE OBJECTIVES

The Navy's Deep Ocean Technology Program (DOT) provides broad scope technology developments to improve the Navy's ability to perform its undersea missions. CEL established the performance requirements for the coaxial wet connector on the premise that an in-line connector should be electrically and mechanically as nearly like the cable it serves as possible. Of course a connector will never be truly identical to the cable, especially mechanically. In some cases this is just as well because the connector can provide some features that are better than those of an uninterrupted cable (such as a waterblock point, an electrical test point, a swivel strain relief, a fail-safe shear point, an attachment point for hardware, or a grab point for handling equipment). From these considerations, the performance objectives of Table 1 were selected for the coaxial wet connector. Figure 1 and Reference 1 also describe SD list 1 cable specifications.*

Table 1. Performance Objectives for CEL-3 Series Coaxial Wet Connectors

Characteristic	Performance Objective
Voltage	6,000 volts DC continuous, corona-free
Current	Conductor cross section to be equal to SD cable (approximately no. 4AWG) even though most SD systems carry only about 0.5 amperes
Impedance	44 ohms characteristic impedance (Z_o) with mismatch within cable manufacturing tolerances (0.7%)
Mechanical Strength	18,000 lb breaking strength in tension 16,000 lb breaking strength over sheaves 10,000 lb before electrical damage over sheaves
Material Compatibility	No chemical or corrosive mismatch with cable materials or cable termination materials
Life	10 to 20 years in place on the seafloor with a total of 30 wet matings without maintenance
Handling	Compatible with SD cable handling systems (sheaves, cable engines, etc.)
Depth	All ocean depths to 20,000 feet
Mating	Mateable by divers, submersible manipulators, or other special actuators.

*The first major application of the connector will probably be by the Canadian telecommunications company Teleglobe Canada, which intends using the CEL designed connector in repair of deep-water cable damage to eliminate the insertion of excessive slack. If carried to completion, this will be the first major change in at-sea cable repair procedures in more than 100 years. Although the specifications for the connector were selected nearly 5 years ago, Teleglobe indicates that only minor design changes will be required to interface with their cable and meet their needs precisely.

DESIGN

Approach

The design approach was based on previous experience in connector development, as well as cable and environmental constraints.

1. The experience gained with the high-power wet connector (Ref 2) indicated that the best wet-mateable connector to handle 6,000 volts DC would be one using an oil-filled system with a wiping O-ring seal and piston.

2. The requirement for low-loss, high-quality signal transmission meant keeping the conductors coaxial throughout the connectors.

3. Because the cable was very stiff, it became desirable to have no rotational constraints within the connector (mating in any rotational alignment and swivelling).

4. The connector diameter was to be as small as possible but large enough to be handled by submersible manipulators.

5. To allow use of the connector in a wide variety of applications, the outer conductor was also insulated from seawater.*

6. In order to provide good interface with existing SD cable systems, it was decided to use the standard SD molded cable terminations during the connector development program (while these terminations are not optimum for this application, they proved satisfactory for the tests).

7. The requirement for dependable, low-loss contact dictated the selection of Multilam (Ref 3) louvered contact bands in an overlapping configuration. This contact selection, in combination with the use of the O-ring-and-piston design, suggested transferring the strength to the outer conductor at the termination and then to an outer shell on the connector halves so that the latch system could be independent of the electrical sealing and contact mechanisms.

8. The objective of long life led directly to use of the oil-filled pressure-compensated design and also made it necessary to minimize any possible corrosion effects by using nearly inert metals such as titanium or gold-plated beryllium copper where possible and plastics for most other parts.

9. The flexible compensators and seals had to be compatible with both the dielectric fluid and the external seawater.

10. Since the connectors were also subject to being installed or otherwise implanted while already mated, it was necessary to ensure that the connectors could not be accidentally unmated during these operations.

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*This is not required in many existing SD cable systems.

Constraints Derived

When the performance objectives and the design philosophy were combined with operational data on the SD cable system and the most probable mating vehicles, it was possible to derive an additional list of detailed design constraints. Although this list appears to be very restrictive, the experience gained during this program has shown that much flexibility in the final design selection is possible and that the various components ultimately chosen to make up the connector can be recombined in several ways to suit other applications as they may arise:

1. The existing terminations have an OD of 5 inches. For handling over sheaves and for manipulator operations, it is best if the connector has a similar OD.

2. The existing terminations have no flexural strain relief for the cable, so the connector must add one.

3. Manipulator grip points must be at least 12 to 18 inches apart or the wrists will interfere with each other.

4. Manipulators can only align and translate connectors very crudely; off-axis rotations to mate are nearly impossible.

5. Manipulator squeeze force is limited to about 300 pounds with grip opening of about 4 inches (typical of SEACLIFF/TURTLE and other remote vehicles).

6. Maximum connector weight is 150 to 200 pounds.

7. Maximum mating force is 150 to 200 pounds.

8. Corona-free internal design allows no sharp edges.

9. Impedance matching requires conductor dimension changes for the various interfaces (e.g., between oil dielectric and plastic structural members).

10. In a coaxial design with the outer conductor insulated, any spaces formed between moving seals must be pressure-compensated (but electrically insulated), or the connectors cannot be unmated at depth because of possible hydraulic locks.

11. Since most seafloor cables are unavoidably laid with tension of up to 10,000 pounds in some locations, the connector must be capable of unmating under these loads.

Evolution From 1974

Several studies and tests were performed on bare SD cable and electrical contact mockups to determine if a wet mating of SD was feasible. The early results were very promising and led to a full-sized connector model.

CEL-3. The first coaxial wet connector built (CEL-3)* was a complete embodiment of the working features of the design. Several materials were not compatible with seawater and most of the internal plumbing was artificially complicated to allow various approaches in the development and testing of the connector. A crude model of just the electrical portion of the connector had demonstrated that the device could be mated wet and still provide proper insulation resistance. Thus, CEL-3 was intended to be a first experimental demonstration of the full assembly of mechanical and electrical functions. The CEL-3 was successfully mated several times at pressure and was mated in air by a submersible with manipulators to demonstrate basic handling capability.

CEL-3A. The CEL-3 model was electrically successful but was mechanically somewhat limited by the complicated internal hydraulics used in the latch and core piston movement systems (described in Reference 4). An improved model suitable for ocean testing (CEL-3A) was built. This version was also fully successful electrically and was mechanically much improved, but the unmating hydraulic squeeze-ring system was still too complex and not fully compatible with the manipulator systems available.

A special termination was also built for this application. It failed after 1 year because of an assembly error but has been repaired and modified for field installation. It is still in service.

While the next design (CEL-3B) was being tested, a need arose for use of the CEL-3A to connect SD cable to a seafloor test facility for an ocean current measurement system being developed at CEL. This was to be diver-mateable in 75 feet of water and to last more than 2 years. The CEL-3A was modified to incorporate a spring-return system for the piston and to allow simple diver operation of the latches. The connector is now continuing in service at 440 volts AC.

CEL-3B. A contract was let for redesign and fabrication of a long-life prototype model. Using a new CEL concept for a spring-return piston, the contractor produced a greatly simplified prototype design, which used somewhat larger, sturdier mechanical elements. This CEL-3B passed all electrical and mechanical tests and fully demonstrated – at the prototype level – the reality of a wet-mateable coaxial connector for SD cable applications.

The as-built CEL-3B design will be used in the discussion of the operating principles of the connector.

CEL-3C. An even simpler, smaller version of the connector (CEL-3C) has been designed and is suitable for applications not requiring insulation for the outer conductor. In addition, a somewhat refined version of the basic unit incorporates minor improvements suggested by the test programs on the CEL-3A and -3B.

*Intended for laboratory use only.

Future. A summary of the various techniques and mechanisms studied during the program but not ultimately incorporated in the prototype are included in the APPLICATIONS section of this report because they would be useful in adapting the design to other applications of the basic wet connector technology.

PROTOTYPE DEVELOPMENT

Figure 2 shows the CEL-3B connector mated and unmated. Figure 3 is a cross section and is presented in color to clarify the boundaries of the various fluid and solid components. The five main subsystems of the connector are described as follows:

1. Core section, with the shuttle piston (1)*, O-ring wiping seal (2), and center conductor segment with its two electrical contacts (3). This is the heart of the connector since it provides the basic elements of electrical continuity for the center conductor and high-resistance, corona-free insulation of that center conductor from the outer conductor and ground.

2. Outer conductor contact (4) and insulating seal (5), with the associated venting and pressure-compensation system (6). This subsystem provides the same features as the core section (continuity and insulation) for the outer conductor but must also compensate the volume f[illegible]d between the wiping O-ring and outer conductor insulating seal to prevent hydraulic lock during mating and unmating. The subsystem is essential if the outer conductor is to carry more than shield currents. The subsystem is also an essential safety element if divers are to handle the connector.

3. Latching system, including the main housings (7,8), latches (9), sliding collar (10) with detent (11), and guide cone (12) to assist in alignment. This subsystem supports and encloses the electrical portions of the unit. It carries the mechanical strength of the cable when needed and provides the interface with the mating vehicle or diver to allow handling of the cable and connectors.

4. Pressure-compensation systems. In addition to the special seawater venting system for the interseal space (6), there must be a system to pressure-compensate the internal part of the female half and to allow for the change in volume caused by insertion of the male pin (13) during mating. In the CEL-3 series this function is incorporated in the termination subsystem. The boot (14), which provides continuity of the outer conductor insulation (jacket), also pressure-balances the oil used to fill both the male and female halves. If new terminations were used so that jacket were over-molded, the male half might not need to be oil-filled at all; the female will still need compensation because its fundamental operation depends on it.

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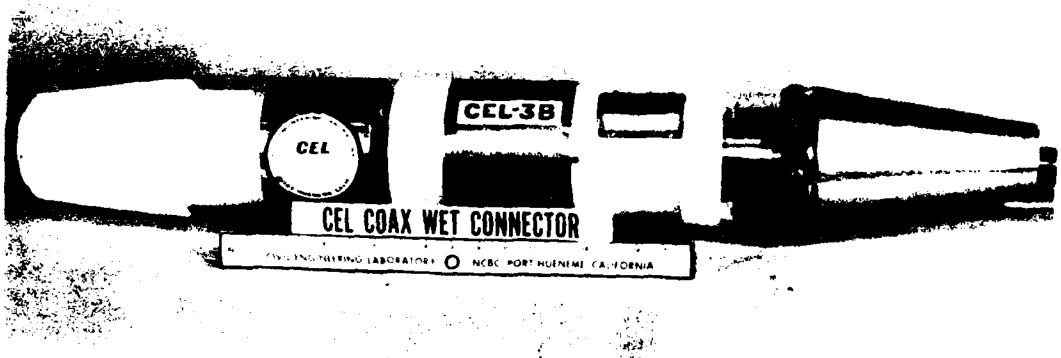
*Numerals in parentheses refer to circled numbers in Figure 3.



(a) Mated.

(b) Unmated.

Figure 2. CEL coaxial wet connector.

5. Terminations, including the strength transition from center conductor to outer conductor (15,16), interface with connector conductors, interface with connector dielectrics, water/oil blocks, interface with housings, and cable bending/flexural strain reliefs (17).

CABLE TERMINATION

In many ways, the design of a mating pair of connectors is a simple exercise compared to the problem of terminating the cable to fit the connectors. Only rarely is a connector required to mate with anything other than its precisely designed and fabricated opposite half. The termination, on the other hand, is often required to accommodate a variety of cables, produced by differing sources, and must adapt to a group of components designed to be linear and continuous. Nearly all of the mechanical loads applied to connectors, especially when mated, must be transferred first through the termination. Unlike the connector faces, which can be rigidly locked together, the termination must tolerate and gently absorb flexural, tensile, and torsional loads, both static and cyclic. To succeed, the termination must be a graduated system, carefully distributing both electrical and mechanical stresses along the transitions from the linear electrical and mechanical conductors to the generally transverse rigid members of the connector half. It must provide tough, tolerant seals between the essentially rigid portions of the connector and the pliable and geometrically complex shapes of the cable members.

The termination section of a cable/connector system is a very complex device and cannot be treated lightly. While it is true that the elements of a series system are equally important, in practice many more "connectors" fail in the termination areas than in the cable and connector areas combined. The termination is therefore the critical element of most cable systems. Much is known about the general principles which must be applied to produce a successful termination, but considerable risk is always taken in applying these guidelines to any specific cable/connector combination or to any new cable design. Each situation presents its own unique problems. The very stringent requirements of the SD cable present a classic example of such uniqueness.

Fortunately however, Bell Telephone and Western Electric have, over the past years, developed a successful termination for SD list 1 cable. While the termination was, of course, not ideally suited to the connector application, it only required slight modification to serve adequately during the development program. With input from models built at CEL and other recent developments in hardware for SD cable, it would be a comparatively straightforward process to design a refined version of the termination to reduce diameter, save weight, lower cost, add strain-relief, and, in general, integrate the termination more smoothly with the connector. This step would be necessary before any large numbers of operational connectors would be produced or in those instances where connector size must be minimized. The termination is presently the largest part of the connector system.

Basic Bell Telephone Type 8E Termination

The terminations used at CEL were modified Bell Telephone type 8E molded terminations. These standard terminations have been used in both commercial and military systems for many years. As shown in Figure 4, these molded terminations anchor the center strength member with epoxy and transfer strength to an outer conductor cone housing. Reference 1 describes how the termination is then normally attached to a 500-pound electronic repeater housing by a flexible gimballed socket. The coaxial configuration is stopped here, and the center conductor is sent via a single-pin penetrator into the electronics housing. In that sense, because the conductors are hooked directly to electronic circuitry, which is tuned and impendance-matched, the termination truly "terminates" or ends the cable electrically. The power is partially consumed by each repeater "load," and the signal is processed and essentially created anew to begin transmission on the next cable leg. Considerable mechanical alteration is also made to allow the flexure needed when handling the large heavy repeaters during storage and during launch or recovery over sheaves and chutes. References 1 and 5 present two other versions of this molded termination.

CEL Modification

To use the 8E with a connector, the anchor molding assembly was cut off at the section shown in Figure 4, and the cone housing cap and all other hardware were eliminated (see Figure 5). Inner and outer conductors could then be threaded directly onto the termination. With the addition of an insulating pressure-compensating boot over the termination outer conductor and a flexural strain relief, the interface between connector and termination was complete.

The only function which the resultant termination did not provide was a water block of the outer conductor. In practice, it turned out that the leakage, if any, was insignificant because of the pressure-balanced design of the connector and the complicated, restricted path through the outer conductor restoration Techniques for providing a firm waterblock have been used with some success in other SD terminations and are under further development at CEL (Ref 6). Further information on gland seal terminations for SD cable may be found in References 7 and 8.

MATING SEQUENCE

The relationships and cooperative nature of the connector subsystems can be understood better by following the mating, operation, and unmating of the connector as described in the next sections.

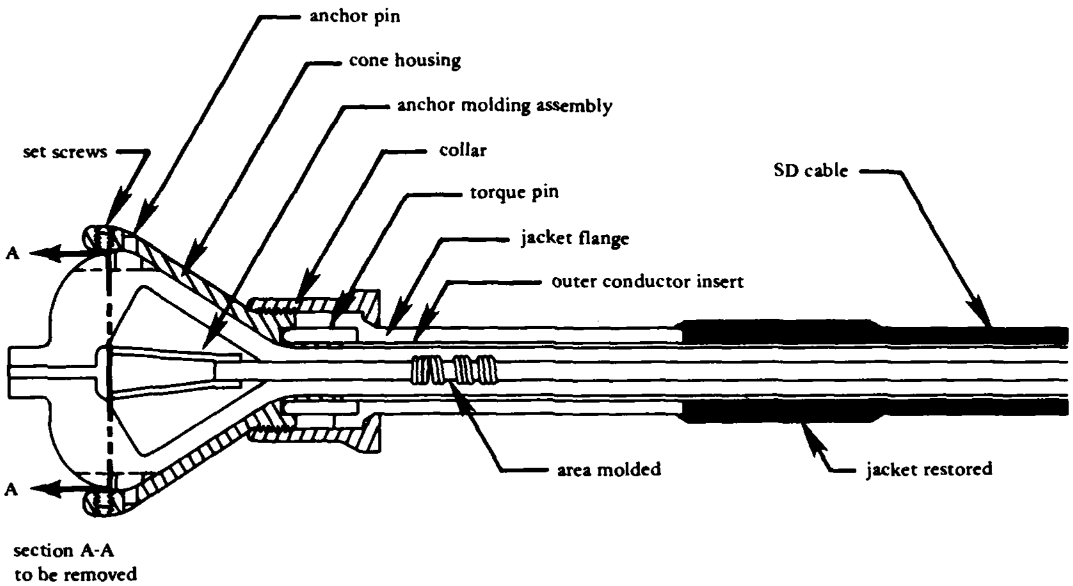


Figure 4. Bell Telephone type 8E termination for SD list 1 cable modified for use with experimental coaxial wet connector.

Figure 5. Modified type 8E termination for use with CEL-3 series coaxial wet connectors.

Preparation

Figure 6 shows the mating sequence. With the connector halves unmated, the shuttle piston in the female half is held fully forward through the wiping O-ring seal by the piston spring (18). Thus, the center conductor (15) is open-circuited because the portion in the center of the piston is not touching the main center conductor. The plastic rod (19) keeps these portions aligned. The connector is therefore "dead-faced"; i.e., the center conductor of the cable is fully insulated from seawater. The outer conductor, however, is in contact with seawater and therefore effectively grounded. The core front bulkhead (20) is sealed to both the shuttle piston and the inner surface of the outer conductor so the dielectric oil in the female cannot leak out nor can seawater leak in. The outer housing of the female has no moving parts. It is made up of the outer shell with its raised latch ring (21) and the insulating portions of the housing. The materials used in all these parts are listed in Appendix B.

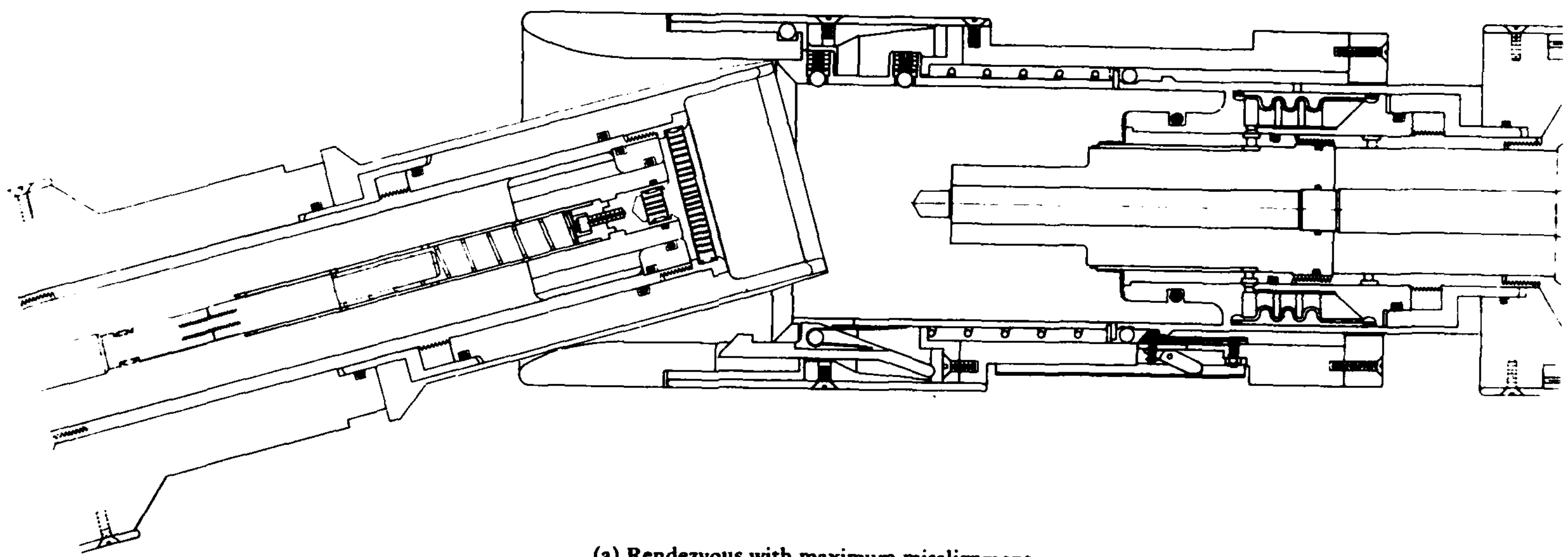
In the male half of the connector the latch collar (10) is held forward by the collar spring (22), and the latches are held in the latched position by their springs (23). The small detent is spring-loaded down over the detent ridge (24) so the latch collar cannot be pulled back unless the detent cover plate (25) is depressed at the same time the collar is pulled back. The interseal venting compensator (6) is in a neutral position. When unmated and underwater, the compensator will naturally flood with seawater. If the connectors are to be mated in air and then submerged, this compensator must be filled with some essentially incompressible fluid to prevent collapse of the compensator during descent because entrapped air compresses. Use of a dielectric oil would be ideal and would also improve the life of the outer contacts.

During installation or handling, the connectors usually would have expendable caps to prevent damage to the faces. These would be pulled off just prior to mating. The connectors are not affected by fine-grained contamination, such as silt or sand, but will not fully mate if large-grained (>1/8-in.-diam) sand, gravel, or shells are caught between the faces.

Alignment

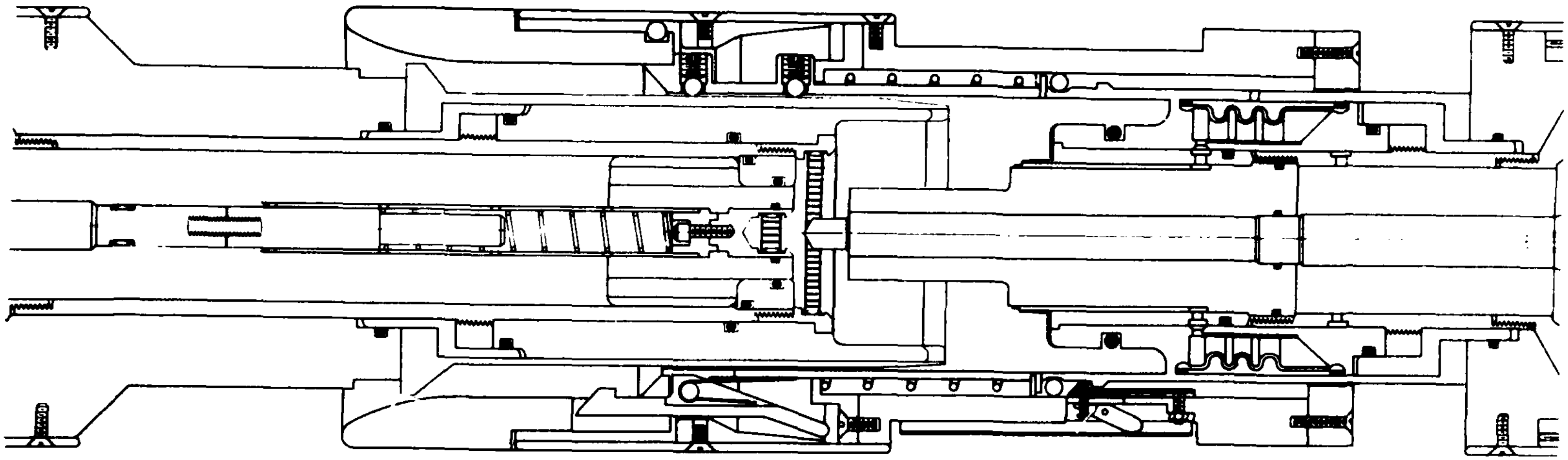
The connectors are gripped by any appropriate system (divers or manipulators) at any desired position on the housings except that the female may not be gripped forward of the termination because the male housing overrides this part during mating. The best grip points are the grooves or flats (26) provided in the strain-relief areas behind the terminations.

The connectors are brought into basic alignment with the female housing starting into the male guide cone (Figure 6a). The connector axes may be misaligned up to 20 degrees and laterally displaced by up to 2 inches when first insertion is made. Note that because of the stiffness of SD cable, this type must be slack to perform the alignment.



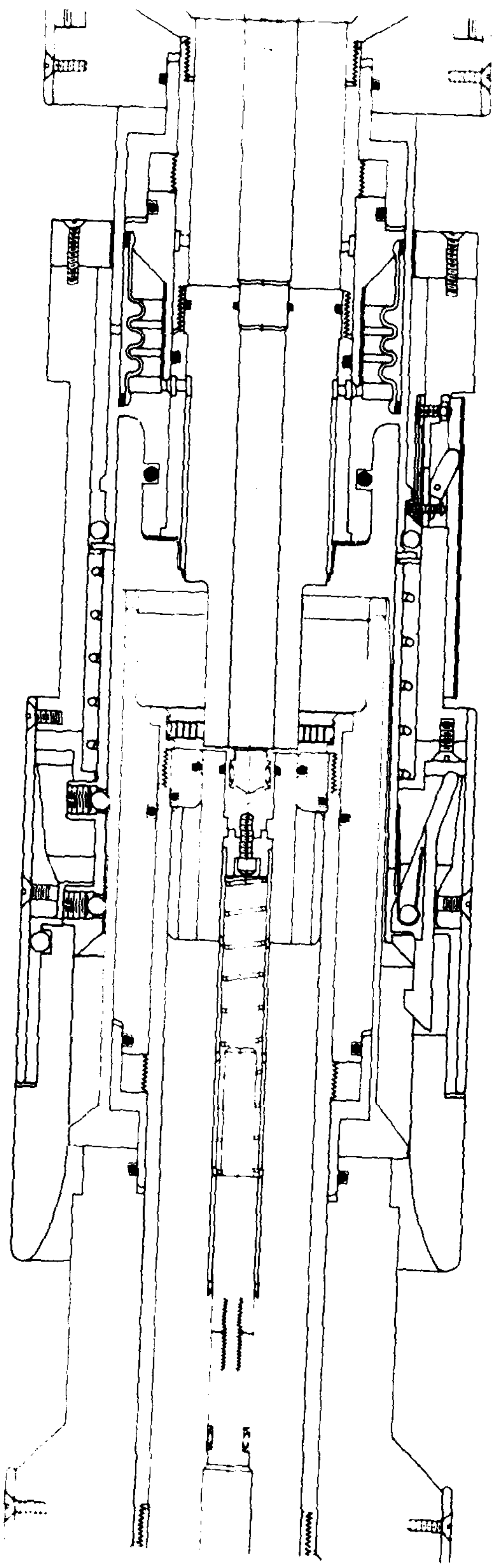
(a) Rendezvous with maximum misalignment.

Figure 6. Mating sequence of CEL-3B connector.



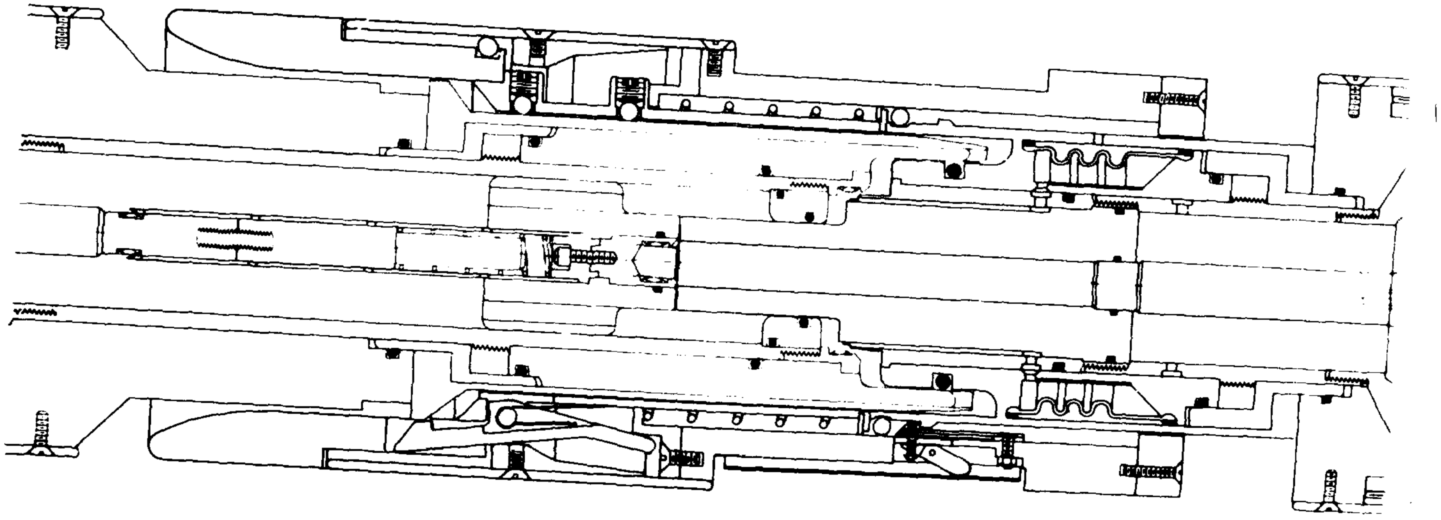
(b) Alignment complete, ready for mating.

Figure 6. Continued.



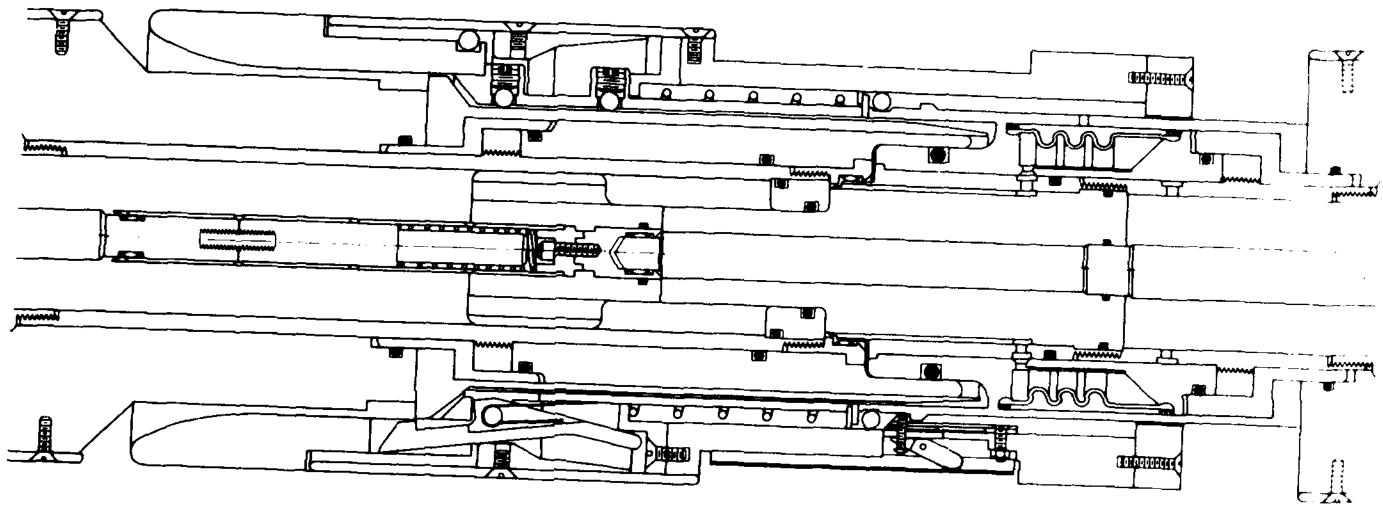
(c) Partially mated, main wiping seal engaged.

Figure 6. Continued.



(d) Partially mated, outer conductor seal engaged.

Figure 6. Continued.



(e) Latches engaging.

Figure 6. Continued.

After the connectors are brought together another 4 to 5 inches, the cone will have reduced lateral displacement to less than about 1/16 inch, and axial misalignment will be down to about 5 degrees or less. Seawater flows out around the female housing and through the small vent holes (27). The male latches are free to lift up as the female housing passes by or is moved off-center against them. Figure 6b shows the alignment completed, with the connectors ready for mating. Up to this point the only forces required of the handling system are those needed to support the weight of the connectors (about 12 pounds for each half in water) and to move the cable (0.3 lb/ft plus bending forces, typically less than about 30 pounds total). This overall total is well within the handling capabilities of most manipulators.

Mating

The first step in mating the connectors occurs when the center conductor of the male pin makes contact with the socket in the center of the shuttle piston. Using the Multilam contact band (3,4) allows good contact with very small insertion force so the shuttle piston spring is easily biased to keep the piston from moving during this insertion. A pre-load on the spring of only 2 to 3 pounds is sufficient. With the pin against the face of the piston, the pin forms an essentially continuous rod through the wiping O-ring seal. The edges of the pin and piston faces are kept fairly sharp, and the diameters are kept identical within ±0.002 inch. Some seawater is trapped within the center conductor contact area, and a thin film is left on the piston/pin interface.

As mating continues, the piston is pushed back into the female, and the male pin slides through the wiping O-ring seal as in Figure 6c. This process is the primary method of excluding seawater from the interior of the female and producing an insulated path between the inner and outer conductors. Note that it is a surface on the male pin that is of concern here, since at voltages of interest (6,000 volts DC) it is primarily a surface breakdown phenomenon that limits the insulation capability, not the thickness of dielectric. Tests have shown that at least 1/2 inch of clean, oil-wetted path length is required to handle 6,000 volts DC without corona. In this design, the length is 1-1/2 inches to improve reliability. Each inch of path length effectively adds 2 inches to the overall connector length because of the spring stroke ratio requirements, but this effect is trivial compared to other elements in the makeup of the overall connector. The O-ring itself forms a rather effective insulated path which will hold a few hundred volts, even with seawater on both sides. This O-ring in service, however, is easily nicked or scored by contaminants. While this does not cause enough leakage in a pressure-balanced system to impair connector performance, it does mean the O-ring cannot be depended on for primary insulation. Mating force begins to increase here as first the pre-load of the spring, then the static friction of the O-ring, then the increasing load are overcome as the spring is compressed. At the fully mated position, this force is about 15 to 20 pounds. As the male pin enters, oil is forced back through the connector interior and into the compensator/boot.

The next step in mating occurs when the outer conductor seal (5) engages. In CEL-3B this is simply a thick O-ring, which insulated the outer conductor to 600 volts with better than 100 MΩ. As this seal engages, seawater is trapped in the space between the outer seal and the main O-ring wiping seal (5,2). Seawater is forced back along grooves in the solid dielectric that forms the male pin and into the venting reservoir (6). Figure 6d shows this action. Note that although this leaves the outer conductor immersed in seawater, the seawater is insulated from the surrounding seawater by the outer seal and the housing and reservoir of the male half. Mating forces must increase by about 10 to 15 pounds to engage the outer seal and keep it moving while forcing the seawater into the venting reservoir.

During the final 1/2 inch of the mating stroke, three things happen simultaneously: (1) the center conductor in the shuttle piston makes contact with the center conductor of the female half to complete continuity of the center conductor; (2) the outer conductors make contact (again using a Multilam band); and (3) the latches ride over the ridge on the female housing (Figure 6e), snapping down into place to complete the mating. The final configuration is shown in Figure 3.

OPERATION WHILE MATED

The primary function of an electrical connector is to provide both electrical continuity and insulation for the conductors. Insulation must be both between conductors and between conductors and ground. In addition to the primary function, the connectors usually must provide some transfer of mechanical strength, especially if they serve as an in-line member of a cable system.

Electrical Operation

Figure 7 shows the primary electrical paths in the coaxial wet connector. In a coaxial configuration the signals are carried mostly on the surfaces of the conductors, while the power (DC or low-frequency AC) is carried throughout the conductor cross section. In a coaxial configuration the inner and outer conductors serve as waveguides, with the dielectric insulation between them serving as the medium of propagation for the electromagnetic waves. Ideally, the connector will appear electrically identical to the cable itself to eliminate any discontinuity in the cable impendance that could produce reflected signals or insertion losses, both of which can severely degrade high-quality transmission systems using SD cable. For design purposes, the impedance of coaxial cable may be shown by the expression

$$Z_o = \frac{60}{\sqrt{k}} \ln\left(\frac{R_1}{R_2}\right)$$

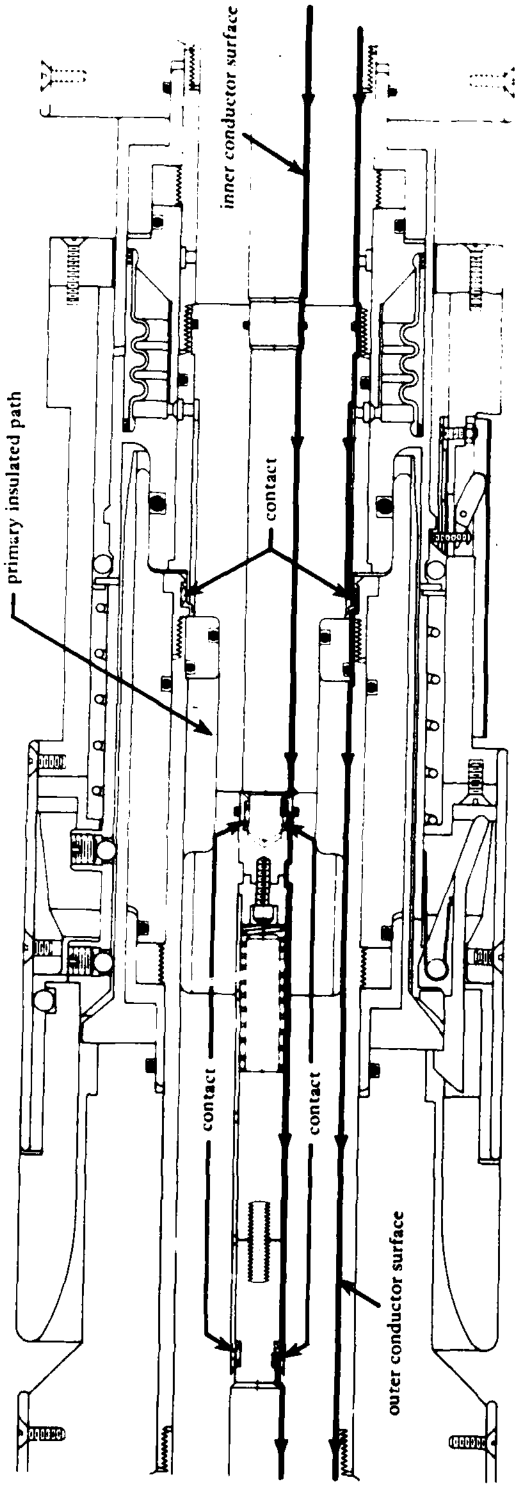


Figure 7. CEL-3B electrical paths.

where Z_o is the characteristic impendance (44 ohms for SD cable), k is the dielectric constant of the insulation material between the conductors (dimensionless), R_1 is the inner radius of the outer conductor, and R_2 is the outer radius of the inner conductor. For SD cable, k is 2.28, R_1 is 1.000 in., and R_2 is 0.330 in. In designing and operating the connector, it is therefore important to ensure that the proper combination of conductor dimensions and dielectric properties are maintained throughout the length of the terminations and connector. For most SD systems the mismatch must be less than 1%. Commercial termination mismatch is about 4% because of the flare on the center conductor. This taper was designed primarily to meet mechanical requirements. Note that minor variations such as the presence of a thin film of seawater between the inner and outer conductor seals and the channels of seawater in the male half do not affect the impendance; only changes which go completely through the cross section are important. Fortunately, the problems of concentricity and roundness that bother cable manufacturers are not significant in connectors because the machining or molding of parts can easily be controlled to close tolerances to accommodate these dimensions.

The center conductor has two series contacts: the first between the center conductor of the female half and the shuttle piston and the second between the front of the shuttle piston and the male pin. As long as good electrical contact is maintained through the Multilam bands, the small gap in the surface at the two interfaces is not significant at the frequencies of interest (up to 1 MHz). This conductor is also the primary conductor for electrical current and is held at potentials of up to ±6,000 volts DC with respect to the outer conductor. Normally, only a few milliamperes of current flow through the system, but in air both the cable and connector can carry over 100 amperes continuous. Probably double that current could be carried in water. Since the conductors are only effectively no. 4 AWG in cross section, however, the power losses in the cable would probably limit the usable current levels to 50 to 100 amperes. Heating is not likely to be a problem.

The inner conductor is supported by the shuttle piston and the core front bulkhead, and the primary insulated path is shown in Figure 7. If it is assumed that seawater exists in the interface between the male pin and the piston and is present in the space between the inner and outer conductor seals, the critical path is from the wiping O-ring to the end of the male pin, a distance of 1-1/2 inches.

The outer conductor flares out through the termination to allow the increased diameter needed for interference anchoring of the center conductor. It then is reduced in diameter to maintain impedance match and allow packaging of the outer shells and latch mechanisms within the overall diameter limits of the handling systems. In CEL-3B the inner diameter of the outer conductor is 2 inches, but in CEL-3 it was only 1 inch, and dielectric strength was still ample.

The outer conductor, which uses the same type of Multilam band as the inner conductor, has only one contact. The band is smaller than would normally be used for this conductor diameter, but the small band was used to minimize the amount of seawater entrained and to reduce corrosion problems. Even in tests where the main conductor parts were not gold-plated, no corrosion damage was evident after a full year of submergence.

In most SD systems, the outer conductor is primarily a shield and waveguide rather than a current-carrying member, since the system is grounded to seawater, and seawater is used as the return for the small DC currents. In the coaxial wet connector, however, the outer conductor is insulated from seawater to reduce corrosion problems for the contact and to allow a fully floating system in case larger amounts of power or current are desired.

Mechanical Operation

In the terminations, the mechanical strength of the center strength member/conductor is transferred to the outer conductor as shown in Figure 8. This system allows the maintenance of proper insulation between the inner and outer conductors while providing an interference to load the dielectric in compression when the cable is under tension. The molded dielectric is designed so that it cannot creep or cold flow. The diameter of the outer conductor is reduced as discussed previously, and overlapping rings again transfer strength to an outer shell while maintaining insulation – this time for the outer conductor.

This technique effectively isolates all of the electrical contact mechanisms from the mechanical loads of the cable system. It also encloses them in very sturdy housings to protect them from lateral shocks or compressive loads during handling. Since the electrical contacts are all overlapping designs, a total of more than 1/4 inch of freedom is allowed for movement along the connector axis while electrical contact is maintained. This is particularly important since the latches must be designed to have some amount of dead-space or backlash to ensure that tolerance buildups or small contaminants between the connector faces will not prevent the connectors from coming close enough together to latch properly.

The two connector outer shells, when mated, are locked together by three spring-loaded latches that grip the raised ridge on the female shell. CEL-3B is designed so that any one latch will hold the full cable breaking strength. This interface also allows the connectors to swivel when not under heavy tension and makes the latching independent of rotational orientation of the halves. This is important during mating and general handling. The latches are <u>not</u> designed as bearings. If it is desired to use the connectors as an <u>in-line</u>, full-load swivel it will be necessary to include some form of bearing system, probably in the female latch ridge. The Multilam contacts are serviceable as low-speed rotating contacts without modification.

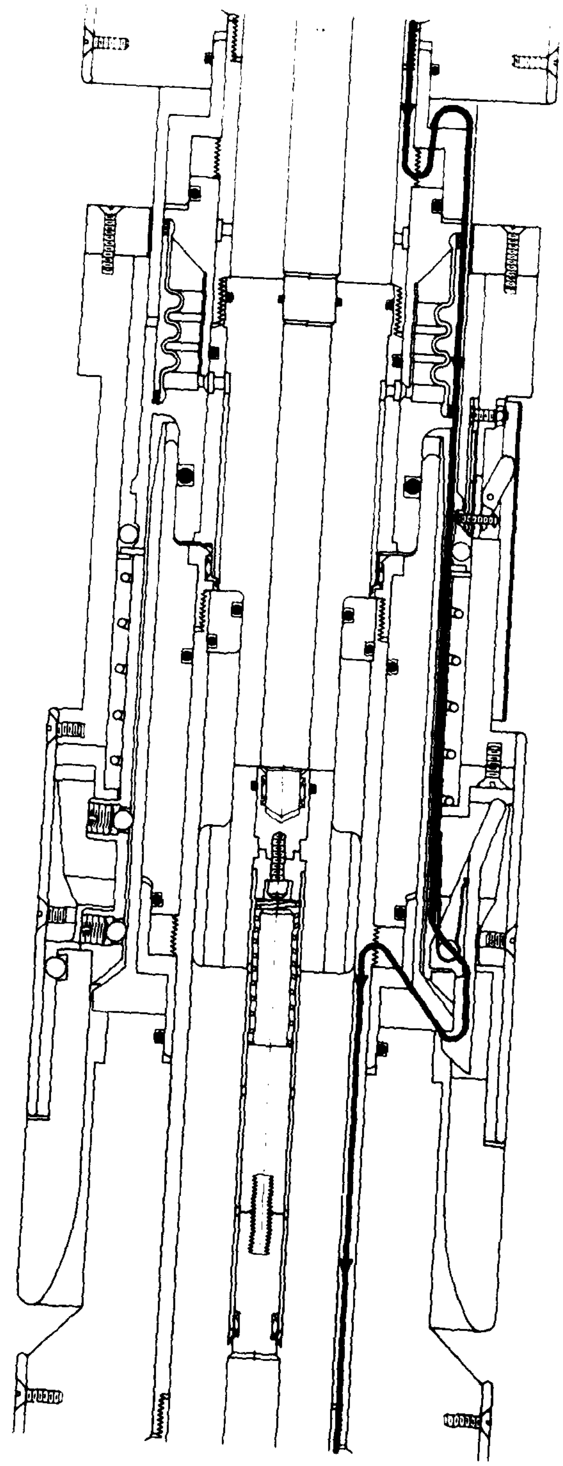


Figure 8. CEL-3B mechanical strength transfer.

Strength passes on through the male shell, via a similar overlap to the same type of termination as that used in the female.

The connectors are held concentric by both the O-ring seals and a series of nylon ball bearings (28) located in the male shell. These bearings reduce friction, allow easy egress of water and contaminants during mating, and help prevent side-loads on the O-rings that would cause leaks after mating.

The detent (11) is in place in the latch collar when the connectors are mated and prevents the collar from being accidentally pulled back as the connectors are handled. The collar is free to rotate and will operate in any position. The collar encloses the latches to prevent damage but is open inside with large clearances to reduce vulnerability to jamming from fouling, rocks, sand, or other debris. The stops (27) prevent the collar from jamming its spring or coming off the latches and also ensure that external fouling will not prevent the collar from being pulled back far enough to release the latches.

UNMATING SEQUENCE

To unmate the connectors the detent must be released by squeezing the cover plate over the detent and the latch collar must be pulled back about 2 inches. This releases the latches and allows the piston spring to push the connectors apart.

In CEL-3B, the groove in the latch collar and the height of the detent cover plate are matched to the ID of the tools used by manipulators on TURTLE (DSV-3) and SEACLIFF (DSV-4) so that no matter what the latch collar orientation, closure of the gripper in the groove will release the detent. Because of the connector mass and the on/off type of control used for the manipulators, it was usually possible during the tests to unmate the connectors with only one arm, even when cable was slack.

Divers can also operate the connectors by hand when the cable is slack. For tensioned cables, divers should use a pair of tongs for safety; the latches must be balanced carefully to limit the lateral force required for unmating.

The connectors may be unmated with the cable under any tension up to the working limit of 10,000 pounds. The latches move slightly over center when releasing, so more pull force is required on the latch collar at higher tension. On the CEL-3B model, forces range from 20 pounds with the cable slack to 576 pounds of static pull at 10,000 pounds of tension. The 250-pound static capability of the TURTLE/ SEACLIFF arms would limit this model to unmating at a maximum of 2,700 pounds of tension, but with sharp movements of the arms they could probably unmate at any tension. The one-armed operation would probably be desirable in this case to reduce chances of vehicle damage because cable movement when parted under tension can be considerable (up to 90 feet on level seafloors, more on slopes). This effect is discussed in detail in Reference 9.

For repeated matings it is imperative that the shuttle piston return with the male pin and seal through the wiping O-ring as the unmating occurs. This prevents oil loss and keeps out seawater. With slack cable this is no problem because the spring is pushing the connectors apart. With the sudden movement of parting under tension, however, the piston must be free to respond quickly; the piston spring force must be as high as available mating forces will allow. The piston head must be perforated to allow easy oil flow, and the oil viscosity must be low. In addition, it helps to have the access to the female compensator and the male reservoir restricted. The sizes chosen provide little resistance at the slow speeds of mating but are much more restrictive to fluid flow at high rates than are the passages through the shuttle-piston head. This resistance provides a partial dynamic brake on the unmating to slow it down enough to ensure that the piston follows. Laboratory tests of parting at tensions up to 10,000 pounds showed this technique to be effective; no more than a drop or two of oil was lost in 10 consecutive tests.

During unmating, the reservoir in the male half empties seawater into the space between the inner and outer conductor seals. The reservoir is designed with a nominal volume large enough so that even if the water initially charged into the reservoir during mating should leak out, the flexible bladder has room enough to collapse below its neutral position and allow unmating without generating a hydraulic lock.

Note also that this connector breaks electrical contact only in fluid-filled, pressure-compensated, sealed chambers. Both inner and outer conductors are, therefore, explosion proof. After unmating, the female center conductor is fully dead-faced so the connector may be energized for system tests. This feature also provides safety for divers or vehicles operating the connectors.

TESTING

The testing for the various pieces of hardware created during the coaxial wet connector development was designed to meet the following objectives:

1. Demonstrate feasibility of the overall concept of making a wet connection of SD cable, with consideration for long-life applications.

2. Demonstrate compatibility of the connector with the electrical and mechanical performance of SD cable.

3. Demonstrate compatibility of the connectors with the handling and mating systems to be used (submersibles and divers) both on deck and in an actual ocean environment.

4. Develop sufficient understanding of the operating principles of coaxial wet connectors to provide design guidelines for expanding the basic prototype concept to other applications.

5. Demonstrate use of a prototype in the ocean (the final objective).

There was no specific program with needs or requirements to drive the work into elaborate (and expensive) development of a single design for production use; therefore, the emphasis was on gathering a wide base of knowledge about several forms of the device. Thus, to establish reliability data, many short-term tests of individual items were planned rather than long-term tests of several duplicate models.

With these objectives in mind, tests were performed first at the component level, then at the experimental mockup level (CEL-3), and finally with each of the three different versions of the prototypes (CEL-3A, -3A Mod 1, and -3B). The tests performed are outlined in Tables 2 and 3.

Table 2. Testing of CEL-3 Series Cable and Contact Systems

Type of Test	Operational Conditions/Results of Tests on--	
	Bare Cable	Contact System
Time Domain Reflectometer		
Dry Mate	<<3% mismatch by VSWR	0.5%
Wet Mate	Not applicable	0.5%
HIPOT		
Dry Mate	5 kV <1 μA (500 MΩ)	10 kV <1 μA (10,000 MΩ)
Wet Mate	Not applicable	10 kV <1 μA (10,000 MΩ) After 24-hr soak, seven wet mates
Shielding	No leakage measurable at 0.250 in. offset with both Stoddart high probe and Stoddart search loop at 1 MHz	Not tested
Corona	No RF noise measured at 5 kV, 1 MHz	Not tested
Mechanical Functioning During Air Mating	Not applicable	20 to 30 psi to unmate 5 to 10 lb to mate

Table 3. Testing of Complete CEL-3 Series Models

Type of Test	CEL-3			CEL-3A			CEL-3A (Mod 1)			CEL-3B		
	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date
Laboratory Tests												
Time Domain Reflectometer												
Dry Mate	5.4%	5	6-23-75	3.0%	5	5-76	See CEL-3A			2%	4	4-20-77
Wet Mate	5.4%	5	6-23-75	3.0%	5	5-76	See CEL-3A			2%	3	4-20-77
Hi POT												
Dry Mate	11-kV DC	4	6-23-75	12-kV DC continuous for 2 mo <1 μA (>10,000 MΩ)	2	12-76/ 3-77	See CEL-3A			See P.V. tests	–	–
Wet Mate	10-kV DC	2	6-23-75	After 2 mo 1-2 cc seawater added. 10 kV 200 μA (500 MΩ) for additional 1 mo	2	12-76/ 3-77	See CEL-3A			See P.V. tests		
Corona (wet mate)	8.5-kV AC inception 6.5-kV AC extinction	2	7-75	Not run; hardware in long-term high potentiometer & termination tension tests (Table 2)	–	–	See CEL-3A			Tests not run: priority effort for long-term sea test; design even more conservative than CEL-3	–	–
Pressure												
TDR (wet)	5.4% (no change with pressure) 5,000 psig for 24 hrs, then 13 wet mates at 0 to 4,000 psig	13	4-23-76	P.V. tests not conducted; (squeeze-ring bladder & O-ring problems during in-air check-out tests)	–	8-20-76	See CEL-3A			2% (24 hr at 5,000 psig, then 34 wet mates at 0-5,000 psig-no connector failures)	17	4-20-77

continued

Table 3. Continued

Type of Test	CEL-3			CEL-3A			CEL-3A (Mod 1)			CEL-3B		
	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date
Hi POT (wet)	300V DC 3μA (100 MΩ) (limited by P.V. fittings) 10 kV DC 1μA (10,000 MΩ) before/ after	–	4-23-76	P.V. tests not conducted: squeeze-ring bladder & O-ring problems in air check-out tests in test frame	–	8-20-76	See CEL-3A			12-kV DC 300-1,000 MΩ (24 hr at 5,000 psig, then 34 wet mates at 0-5,000 psig–no connector failures)	17	4-20-77
Tension Static	10,000 lb 5 times	5	7-1-76	Tension/un-mating tests not run: poor results on test frame & vehicle air matings	–	–	Tension tests not run: unsafe for divers & not required for CMS application	–	–	10 cycles 2,000-10,000 lb (4-25-77) 7 cycles 2,000-10,000 lb (5-12-77)	–	Apr-May 77
Unmating	Wouldn't release at any load >200 lb (ok when slack)	–	7-1-76	Tension/un-mating tests not run: poor results on test frame & vehicle air matings	–	–	Tension tests not run: unsafe for divers & not required for CMS application	–	–	3 of 10 un-mates successful. Latches hung up on others because collar cocked (4-25-77). 7 of 7 ok-0-10,000 lb w/ modified collar (5-12-77)	17	Apr-May 77
In-Air Mating Manual	30-50 lb mate force (6-3-75) 60-75 lb mate force (6-23-75) (Air wt 53 lb 35 male, 18 female)	13	6-75	Misc. air mates de-bugging hydraulics, improving TDR match & for briefings, etc.	20	Summer /Fall 76	25 lb force. Lowest force, smoothest action of any unit tested. Tested in lab 8-77. Mated on deck at sea 12-77, 3-78.	8	Aug 77-Mar 78	30 lb force. Misc matings de-bugging detent, modifying latch collar, adjusting no. of O-rings in outer conductor seal	40	Mar-Aug 77

continued

Table 3. Continued

Type of Test	CEL-3			CEL-3A			CEL-3A (Mod 1)			CEL-3B		
	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date
Test Frame	80-100 psi internal (450 lb squeeze) required to unmate	10	3-20-76	Mating ok (20-30 lb) but unmating unsatisfactory because of squeeze-ring bladder & misc hydraulic leaks	7	8-20-76	Not applicable			5 cycles Debugging test frame for P.V. tests	5	4-16-77
Vehicle	Mated twice by SEACLIFF; unmated by hand because vehicle hydraulics not sufficient	2	9-15-76	Failed to mate (galled) by TURTLE (9-15-76) Modified shell mated easily by TURTLE but still no unmate because required force too high	5	11-24-76	Not applicable			5 mates by SEACLIFF with only one arm working. <10 sec to lift, align, mate	5	5-31-77
At-Sea Test Conditions and Results												
Wet Mating Diver	Not applicable			See Mod 1			Wet mated by divers on CMS structure at 75 ft. System repowered after electrical checks ok	1	11-15-78	Not tested by divers because of priority effort for long-term sea test & because of good performance in all other handling tests		

continued

Table 3. Continued

Type of Test	CEL-3			CEL-3A			CEL-3A (Mod 1)			CEL-3B		
	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date	Operational Conditions/ Results	No. of Matings	Date
Vehicle	Not applicable			5 mates by 3 operators at 240 ft by SEACLIFF (mechanical only)	5	12-17-76	Not applicable					
Long-Term Immersion	Not applicable			See Mod 1	–	–	Installed (cable laid) in 75 ft of water. TDR ok; Hi POT 6 kV DC, <1μA (6,000 MΩ) 8-77. Mated/powered 12-77. Inspected on deck 3-78 and 10-78. Termination repaired 11-78.			Installed on seafloor at 6,000 ft. TDR 2% & Hi POT ok at launch 8-2-77. TDR no change but 5kΩ fault in system (170 VDC at -3B) 10-5-77. No change 12-6-77. Buoy lost prior to 2-21-77.	3 air	8-77

Component Tests

The tests were performed primarily to determine the feasibility of using certain concepts for connector components.

Cable Characteristics. SD cable is manufactured to extremely tight tolerances, and anomalies in cable geometry and material properties are held to a minimum. Although the general equation for cable impedance provides basic guidance, little or no literature exists relating the nature of coaxial connector elements (such as electrical contacts, dielectric interfaces, and other items) to their effect on cable impedance and signal transmission. Table 2 presents the conditions and results of the tests.

In the first test run cable was simply cut through, the faces cleaned smooth, and a butt contact made between the bare cable ends. With the ends held in contact and one-half mounted in an indexing table, it was possible to observe the effect of lateral displacement of the mating faces on electrical performance. With the ends butted snugly together it was possible to displace the faces laterally up to 0.250 inch (25% of the outer conductor diameter and 75% of the center conductor diameter) without any measurable effect on impendance match, corona performance, high voltage DC insulation resistance, or shielding. All RF measurements were at 1 MHz, a typical upper frequency for SD cable. These tests confirmed that for this cable, at these frequencies, precise geometrical continuity was not as critical as imagined and that there was, in fact, room for some distortion to insert contacts without major electrical disruption.

Contact System. With the encouragement provided by the cable test results, a mockup of the inner conductor/shuttle piston was built to include a squeeze-ring for hydraulic operation. The conditions and results are presented in Table 2. The male half was simply a short section of SD cable with the dielectric machined to act as the pin. The contacts were butt contacts. This model was mated in shallow water seven times and verified that the O-ring wiping of the dielectric was a feasible approach for a coaxial design. Pulse-echo measurements with a Time Domain Reflectometer (TDR) showed this section to have <0.5% impedance mismatch and to have excellent high-voltage insulation resistance. The mechanical functioning of the piston was also satisfactory.

Latch System. The next step was to select a latch system to serve as the basis for the mechanical strength transfer system. To minimize the operations required of the manipulator, it was decided to operate the latches hydraulically from the same squeeze-ring system as that used for the core shuttle piston return. This would leave the manipulator with only one required motion to fully unmate the connectors, automatically prevent accidental unmating, and ensure that the system was pressurized so that the piston would always return after the latches were released. A small mockup of a latch system was built, using a latch very similar to a common door latch attached by a linkage to a spring-loaded piston. This way the latches could freely withdraw for automatic latching during mating. Although there was some difficulty with the piston seals, the function appeared to be very smooth, and the operating pressure required was well within design limits.

Fluid Mechanics. Since data were not available on the dielectric constant of mineral oil (USP), tests were run using the TDR and a short section of outer conductor. With the ends capped, center conductors of various diameters were used, and the model was oil filled. A 0% mismatch was obtained with a center conductor diameter of 0.350 inch, which implied a dielectric constant of 2.05 (unexpectedly low for a hydrocarbon).

In later tests on the CEL-3A, a derived value of 2.19 was obtained. This variation may be explained by variations in temperature and quality control of the fluid supplier. If a connector with a <1% impedance mismatch is built, the quality of the fluid will have to be tightly controlled.

CEL-3 Experimental Model Tests

The CEL-3 was the first complete assembly of all the basic features of the coaxial wet connector. It was intended as a laboratory model only, so the materials used were not compatible with sustained immersion in seawater. In most cases acrylic was used for plastic parts to allow easy diagnosis of problems and inspection of functions. Rubber parts were usually glued together from neoprene wet suit material, rather than being molded, to save time and expense. Details of construction were reported in Reference 4.

In the laboratory tests all electrical tests were satisfactory except that impedance mismatch was slightly greater than desired (see Table 3). The connectors worked well at pressure and could be handled manually with no trouble, but did not do well when handled by submersible because the unmating squeeze force required was higher than the manipulators could provide. The latch system was also unreliable and would not release under tension. In addition, testing showed that the design was very cumbersome to assemble and disassemble and had too many parts to be reliable in field service.

CEL-3 served as an important first step in the development program, and the good performance of its critical electrical components was encouraging.

CEL-3A Prototype Tests

The CEL-3A was designed to be compatible with sea testing for moderate periods (1-5 years) and was generally compatible with seawater environments. It included stainless steel external parts, gold-plated contacts, molded rubber bladders, and Delrin plastic or PVC external blocks. The squeeze-ring hydraulics concept was still used but with simpler internal piping, a better piston size and squeeze-ring size to reduce required squeeze forces, Multilam contact bands, and simplified construction throughout. In addition, a venting reservoir was added to compensate for the space between the inner and outer conductor O-ring seals.

The center conductor diameter was refined to produce a better impedance match as discussed in the section on component testing. The TDR gave an improved reading of 3% for the overall connector. CEL-3A was also used for a 2-month test at a sustained voltage of 12 kV. It showed no degradation. With the insertion of seawater directly into the space between the piston and the core front bulkhead, leakage current increased slightly, but resistance remained greater than 500 MΩ for the month remaining in the test. This served to demonstrate that the connector is tolerant of considerable seawater leakage. In general, it was found that, until the connector is fully flooded so that seawater actually bridges the space between the inner and outer conductors, the insulation resistance will remain acceptable. Since the amount of water required to do this will depend on whether the connector is vertical or horizontal, it may be useful to know the intended application before making final designs for interior bulkheads and transverse dielectric faces; if the connector is to be used vertically it may be desirable to add convolutions to these faces to act as sumps for any seawater leakage.

CEL-3A generally operated better mechanically than CEL-3 but was still not adequate. The connectors jammed upon mating in air by the TURTLE submersible. With some modification to the exterior shell clearances this problem was solved, but the squeeze forces necessary were still too high for unmating.

The units did, however, meet one major milestone - an underwater mating at sea by submersible. Figure 9 shows the setup for the test, which was purely a mechanical handling/mating test, with no electrical monitoring and no squeeze-ring unmating. The connectors with 100 feet of SD cable on each half were chained together and lowered to the seafloor in 240 feet of water. The submersible approached the units, straightened the cable on one-half which had been bent by dragging during implant, and mated the connectors. A total of five matings were performed in a 1-hour period. Two operators performed one mating each, and a third operator performed three mates. The mated connector is shown in Figure 10. In picking the connector up from the seafloor the vehicle grabbed the cable instead of the connector because of trouble with the parallel-jaw manipulator. The cable was damaged, and the outer conductor was actually parted at that point. The compensator boot was pulled back from the termination and would have caused considerable seawater leakage with electrical failure resulting if the units had been operational. As a result, the next connector generation was designed with plastic strain relief blocks and easy grip points behind the terminations both to simplify the gripping operation and to protect the cable/boot.

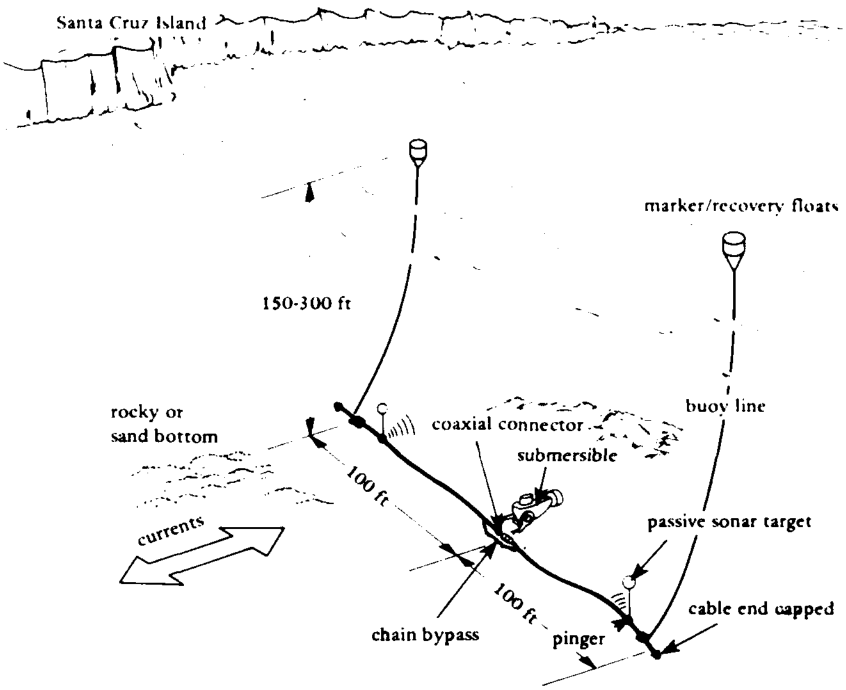


Figure 9. At-sea mating test setup for coaxial wet connector CEL-3A.

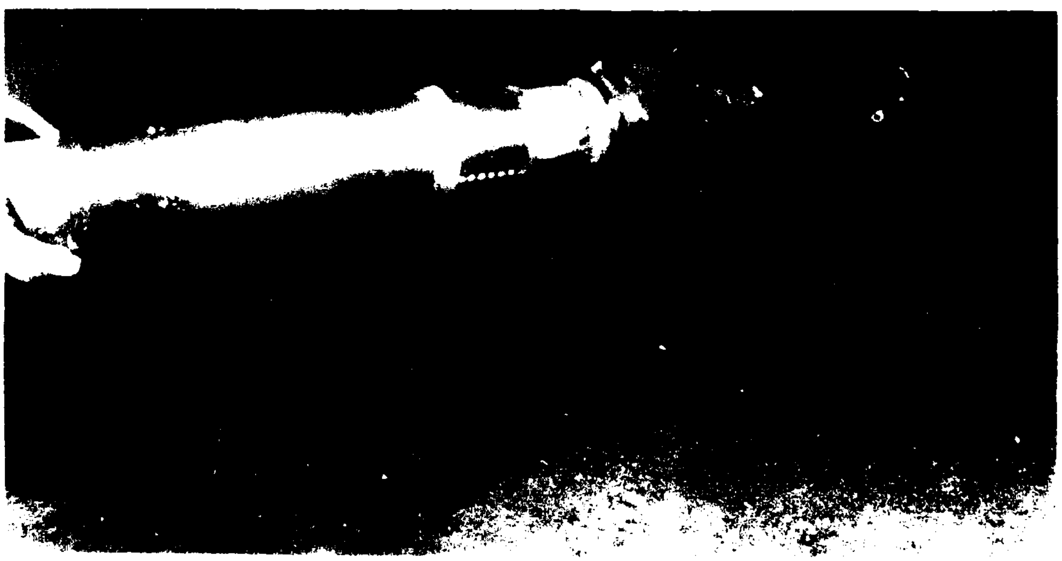


Figure 10. CEL-3A mated at 240 feet using SEACLIFF submersible.

CEL-3B Tests

The CEL-3B was the final prototype in the series. Although refinements and variations developed during the test program, CEL-3B represents a complete working model of the CEL-3 concept. It passed all the laboratory and field demonstration tests and together with the various lessons learned from the other models would serve as the basic design for any future development. It is not to be construed as a production model because the testing has not established full reliability data. Since there was only one complete model, tests were only carried far enough to demonstrate that the connector meets the basic performance requirements. Total mating cycles were limited to just over 100, and mechanical tests to destruction or significant wear were not performed. The hardware was generally well cared for to ensure that it would be available for the entire series of tests and demonstrations.

It is significant to note, however, that the hardware did very well in the tests performed and met all the requirements with apparent ease. Despite a fair amount of handling in the laboratory and at sea, the connectors survived the variety of bumps, drops to the deck, and shock ummatings under tension with no damage.

The electrical performance of the CEL-3B was the best of any of the models. An impedance mismatch of 2% was obtained, and this was limited by the terminations used, not the connector. With improved electrical penetrators in the pressure vessel the connector was tested to 12,000-volts DC under pressure for a total of 34 wet matings at 0 to 5,000 psig. Neither impedance match nor high voltage insulation resistance was measurably affected by the pressure cycles.

CEL-3B was the first connector of the series to unmate successfully under tension. On the first few tries the latch collar was not adequately centered by its bearings so the latches did not withdraw simultaneously. Once the collar cocked off center, the force to complete the unlatching was more than could be provided by the weights available (over 600-pound force). The tests did demonstrate that even under the shock of releasing two of the three latches under tension, any one latch could hold the full 10,000-pound strength of the cable working load. The connectors were not pulled to destruction but were designed to hold more than the cable breaking strength (18,000 pounds).

With the latch collar modified to make it more stable, the connectors successfully unmated seven of seven times, at tensions ranging from 0 to 10,000 pounds. Figure 11 shows the results. These latches had a slight over-center movement built in to ensure that increased tension would not override the latches. This is not a problem with the TURTLE/SEACLIFF manipulators because their "bang-bang" control allows them to exert considerably more force than their static maximum of 250 pounds. In normal use they could unmate the connector at any tension. Some of the smaller manipulators would be limited, however, so some improvement in this features, depending on the application, may be warranted.

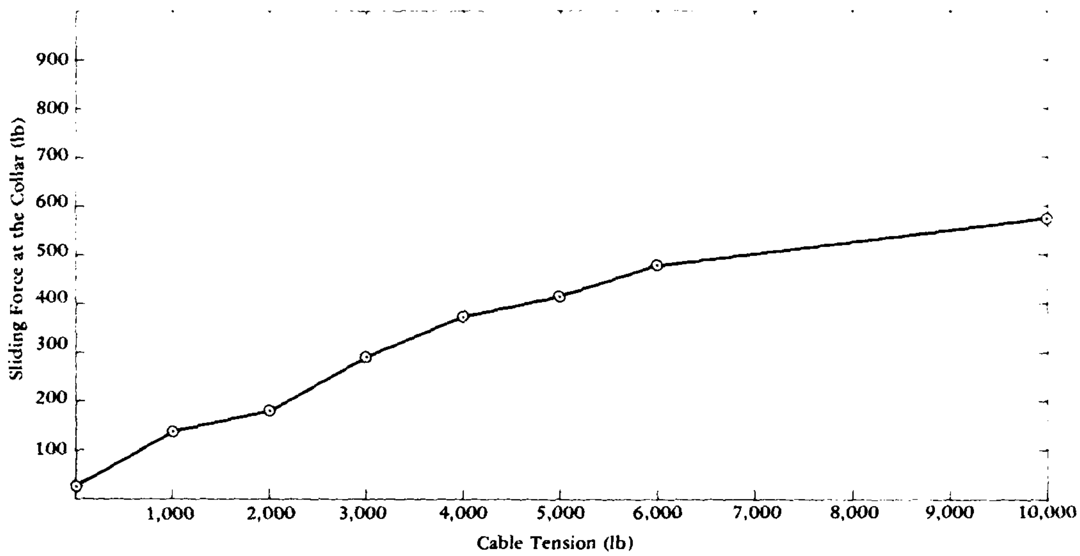


Figure 11. Test results of CEL-3B unmating under tension.

The in-air handling and mating of the CEL-3B was very smooth; both manual operations and manipulator tests were easily performed. No hang-ups or incomplete matings occurred in any of the tests run. The mated connector pair weighs 29 pounds in air without cable or strain relief blocks attached. Total lift force to support the mated pair with strain relief blocks and about 10 feet of cable on each end is 40 pounds in air. Normally, two persons would be necessary to mate or unmate the connectors. Both the weight per half and the large diameter of the grip points are slightly more than can be handled with one hand per half. The manipulators had no such limitation. In five consecutive tests by TURTLE in air the connectors were mated with no trouble. Typical time elapsed – from beginning to pick the connectors up from the floor to having them mated – was 10 seconds. The process of grabbing the connectors may be expected to take somewhat longer at sea because of maneuvering requirements; but, once the connectors are gripped, the mating should not take more than a few seconds (with slack cable).

The major test performed on the CEL-3B was an at-sea demonstration with the connector under 5,000 volts DC, while operating in an SD cable system on the seafloor at 6,000 feet. The test life was to be 1 year. Figure 12 shows the test arrangement. The connector was installed in-line on SD cable. The cable was terminated open-circuit approximately 100 feet past the connector. The open-circuit configuration allowed applying high voltage without drawing significant current. The spacing from the end allowed resolution of the connector with a

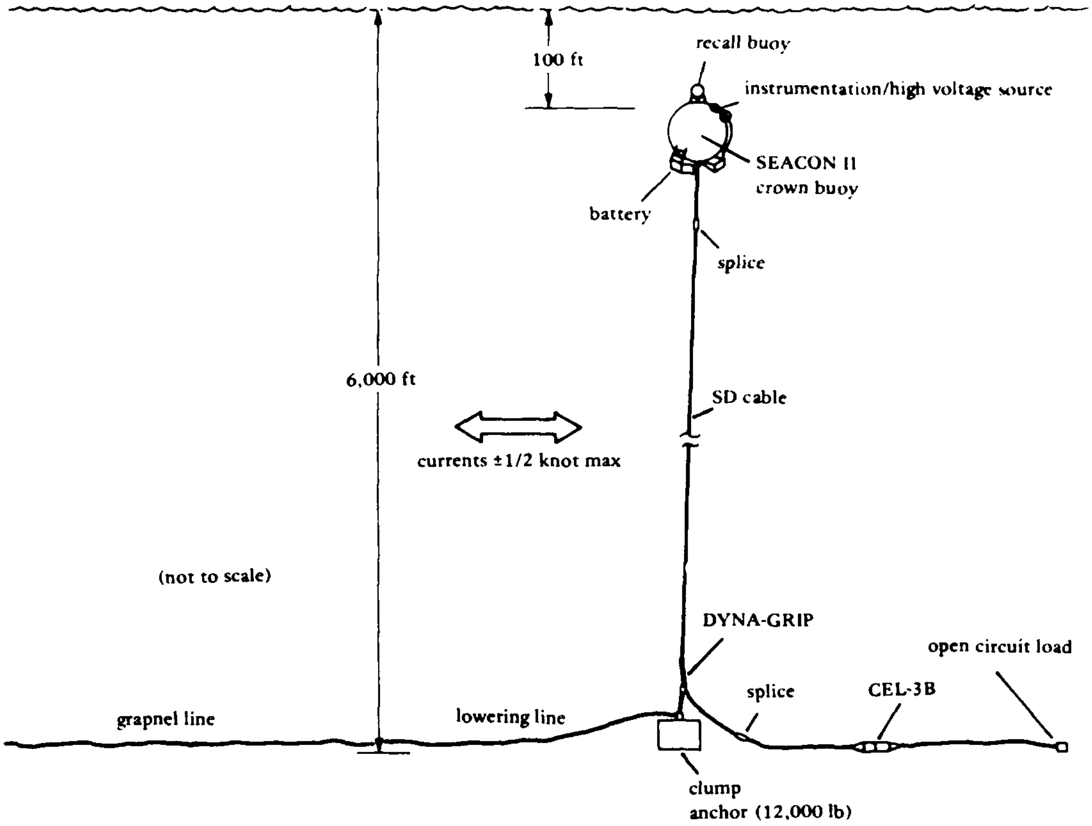


Figure 12. CEL-3B long-term deep ocean test setup.

TDR while taking measurements from the surface, over 6,000 feet away. The cable was gripped with a Dyna-Grip stopper and clevis, which was shackled to a clump anchor. The SD cable then served as a mooring line for an 8-ft-diam subsurface buoy. With large lead-acid battery packs suspended from the buoy and with the interior partially flooded for ballast, the buoy provided a static tension in the vertical SD cable of 4,500 pounds at the surface termination, 2,670 pounds at the seafloor. Battery power was supplied via a 250-foot umbilical to a small instrumentation housing which was normally stowed inside the hollow center well of the buoy. The instrumentation housing was also connected to the SD cable by means of RG-8 coaxial cable. Inside the housing the 32-volt DC from the batteries was stepped up to 5,000 volts DC and applied to the coaxial cable. Applied voltage and leakage current were measured and recorded within the instrumentation housing.

Batteries were designed to supply power for 6 months to 1 year, depending on leakage current. Each month, the instrument package was to be brought to the surface by divers so that the data could be recovered. At that point the RG-8 cable could be disconnected from the package and a TDR applied to look down the entire coaxial cable system and inspect the cables, splice (RG-8 to SD), connectors, and termination (end fitting). This setup would also allow direct monitoring of the connectors from the surface while they were being mated by submersibles.

The connector and test setup was originally installed in August 1977 and was electrically operational by September. A partial short circuit (about 5,000 ohms to ground) in the circuit produced enough current in the system to cause a major voltage drop across a protecting resistor. This resulted in only about 200 volts being applied across the connector itself by the test system. The connector did, however, withstand a 5,000-volt DC test in the first test after implant. TDR measurements showed the impedance of the connector did not change significantly, so it is postulated that the short occurred at the open-circuit termination at the end of the SD cable. TDR measurements are not very precise at large impedance mismatches such as open circuits, and a 5,000-ohm open circuit appears very much like a good circuit under these conditions.

This open condition remained unchanged until sometime in January 1978 when the buoy broke free. The electrical portion of the test was thus aborted after about 4 months of operation.

Single dives were made by the SEACLIFF on each of two occasions: one in March 1978 and the other in March 1979. On the first dive the test equipment was not located, but in March 1979 the submersible located the lowering wire in the predicted location. Unfortunately, the submersible malfunctioned and had to discontinue operations at that point. Because of heavy scheduling of the submersibles through the following summer and fall no further attempt has been made to recover the connector. The partial success of the March 1979 dive and the successful demonstration on that dive of a special hydrostatic cable cutter able to cut the SD cable provide optimism that the connector is still in place and can be recovered when submersible services are available. Because the test will be well over 2 years along by the time recovery occurs, it has been decided not to attempt a mating on the seafloor but rather to recover the connector intact for careful laboratory study and analysis. This will allow isolated study of the aging process of the connector without any possible confusing damage or distortion which the mating process might cause. Results of these laboratory tests and possible future field operations will be reported separately.

CEL-3A Mod 1 Tests

Although the CEL-3A had not done as well mechanically as desired, the hardware did eventually prove itself and, in fact, was the first of the CEL-3 series to actually see operational use. The problems with the connector all centered around the complex hydraulics involved in the squeeze-ring system. When the CEL-3B was conceived and built, it showed that these problems could be eliminated by going to a spring-return system for the piston and a rather simple quick-disconnect type of external latch system. By the time the need for the CEL-3A Mod 1 appeared, the CEL-3B unit was in the ocean undergoing long-term tests. Therefore, it was decided to modify the CEL-3A to incorporate the problem solutions learned from the CEL-3B and to make it mateable by divers.

The Current Measurement System (CMS) test facility application had only a 2-year life requirement and was accessible for repair if needed, so the connector hardware materials were suitable. The application was much less rigorous than the primary design requirements because of the short life, lack of applied cable tension, low voltage (440 volts AC), diver mating, and ease of access for maintenance. The modifications included a piston return spring external to the outer conductor and elimination of the squeeze-ring hydraulics, except for service as a pressure-compensating bladder. In addition, several holes were added around the male shell to allow divers to unmate the connectors by pushing the latches manually with two pins. With these modifications and a CEL-designed field-installable termination, the unit proved very easy to handle and mate. With the exception of a minor sticking problem with one latch, the connector has operated without problems for nearly 2 years, through four on-deck matings/inspections, one wet mating, and a dozen or so dry matings during test and checkout. Figure 13 shows the connector in the mated position on the CMS shallow water test facility power distribution box. The connector had been submerged about 2 years and was still operable, despite the fouling.

Testing Summary

Over a period of 4 years a total of 229 recorded matings of coaxial wet connectors were performed, with probably a hundred more occurring during general handling and checkouts. A total of 72 matings were wet, 47 of them at pressure. All of the wet matings were successful. A total of 92 (37 wet) matings were performed on the final design of the CEL-3B. All of those were also successful. While this is not a particularly large number of mating cycles, it is important to remember that these were usually performed in groups of from 1 to 10 cycles, so that the variety of conditions and designs tested is quite large.

The CEL-3 series has demonstrated it can meet all of the prototype design requirements under laboratory and short-term field conditions. The only two areas of performance not tested were (1) at-sea handling of the connectors with standard SD cable-laying equipment such as linear cable engines and stern chutes, and (2) long-term life (5- to 30-year range). In all other respects, the CEL-3 connectors have demonstrated their full compatibility with SD and similar cable systems, including the cable itself and the vehicles which might be used to handle it underwater.

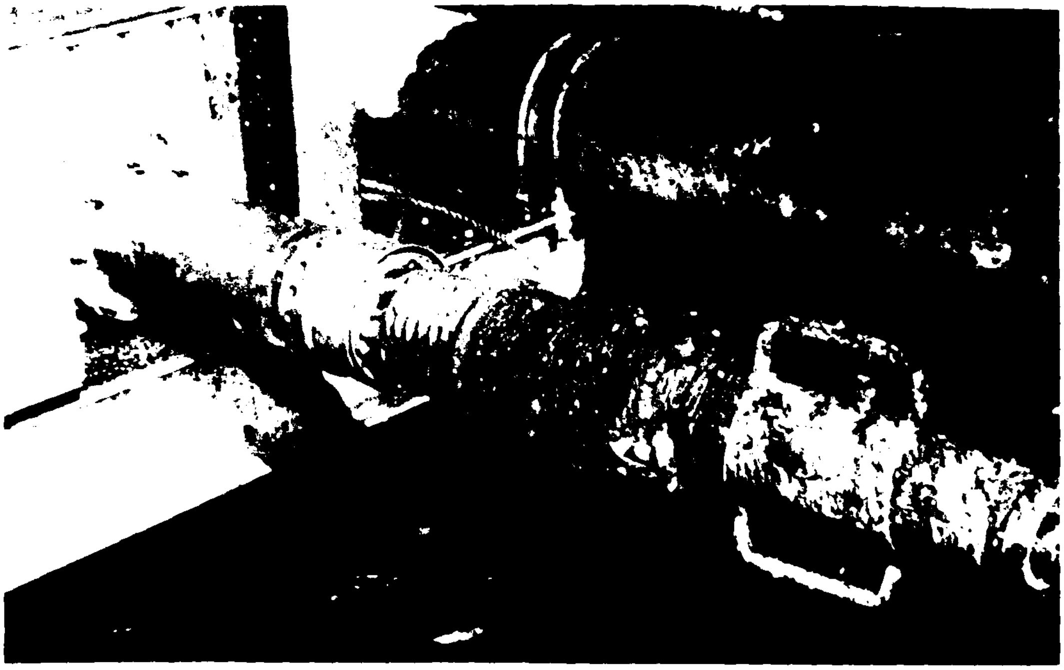


Figure 13. CEL-3A Mod 1 on CMS structure after 1 year at 75 feet.

APPLICATIONS

The idea of wet-mateable electrical connectors has been around for more than 25 years, but only in the past 5 to 10 years has the hardware been developed sufficiently and the need increased enough for both military and civilian designers to actually consider wet connectors as a practical option in system design. Appendix A describes this general development in detail.

The CEL-3 series coaxial wet connectors are designed to be compatible with SD cable and, with minor modifications, would also interface with many other large specialized coaxial cables such as SF, SG, 1.47 LW* or with any other coaxial system such as smaller range cables and vehicle umbilicals or tethers. It is therefore appropriate to consider just what new options are now opened by the development of this new class of connectors.

*Used by the United Kingdom.

General

A connector is an intentional break point in a system - an interface which is fully controlled and self-contained. It is a series element. It mechanically and electrically separates systems - cable from cable, cable from structure. Connector mating is reversible and repeatable (in contrast to a splice, which is installed one time only and is irreversible).

The basic features of connectors give them great impact on all aspects of a system. Their strength (being a series interface) is also their weakness because a connector failure becomes a failure of whatever system it serves. It is imperative, therefore, that connectors be considered fundamental elements of the entire structural or vehicular system from the earliest conceptual work right through design, procurement, fabrication, assembly, installation, test, monitoring, operation, maintenance, and final performance analysis. The penalty for either ignoring connectors or misapplying them can range from minor inconvenience to major system failure. The advantages of properly applied connectors can include improved system reliability; reduced costs; more flexible system operation; improved safety; and, in many cases, development of a capability that simply would not exist without connectors.

Beyond the basic benefits of connectors, wet-mateable connectors offer specialized features and benefits because cable installation from the surface is always risky and expensive. Underwater cable maintenance (though important because of the corrosive environment and young state-of-the-art) is nearly impossible without wet connectors because recovery of most systems is even more costly and risky than installation. Some examples of how wet connectors, and specifically CEL-3 coaxial types, might be applied will illustrate.

New Installations

As previously discussed, connectors are an integral part of a system and can normally be used to best advantage when included in the basic system concept. Connectors can be put at critical locations to allow testing during fabrication, assembly, pre-implant, and even after installation. For example, CEL-3 connectors at repeaters of sections of SD trunk line that are prone to damage would allow easy access for in-situ fault location and repair (especially needed for buried cable). The same connectors could be used to remove or replace an entire section if needed, with no degradation in system electrical performance and no added slack.

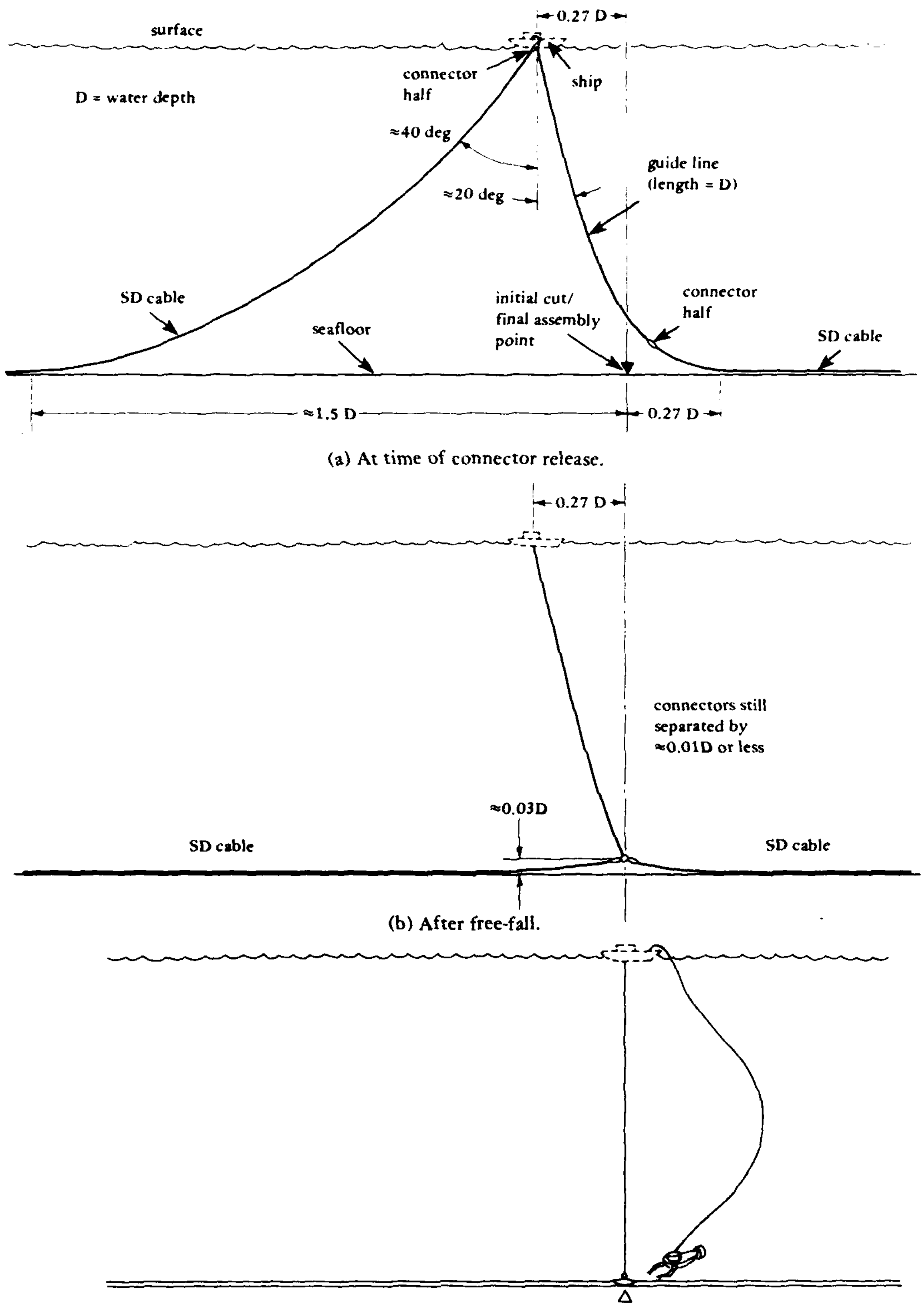
Wet connectors can be used simply to allow separate handling and implant of large system elements so that the implant can be phased and controlled and the size of individual elements can be kept within workable limits. For example, in the proposed Deep Underwater Muon and Neutrino Detection (DUMAND) experiment, the entire structure would occupy nearly a cubic kilometer and would be located several kilometers from dry land in 5 km of water. It would be composed of several hundred vertical sensor strings, each connected through a series of bottom-laid trunks to a central distribution box. This box, in turn, would connect to a shore cable. The need for several kilowatts of power out and many channels of multiplexed data back makes SF or SG cable likely choices for the main trunk with SD or a similar cable for the sea floor trunks. Even if modules used were so large they would be towed out and self-propelled to the seafloor, an estimated minimum of 64 CEL-3 connectors would be needed for this structure.

In some applications it is desired to install or replace single elements or sensors without disturbing the remainder of a seafloor structure whose position has been calibrated. Examples of this include a concept once considered for a project that needed a CEL-3 connector for (1) each of several hundred dipoles to be installed in a large underwater antenna and (2) a seafloor sensor package that needed to be inserted between two sections of SD cable in deep water after the cable was laid. In the latter case the structure/package was too heavy to lower by SD cable, the water was too deep for a combined cable lay and crown-line lowering, and the water was so deep that conventional methods of lifting cable back to the surface would risk cable damage and add unacceptable additional cable slack. Even in shallow water where diver access is possible, the precision of implant or time restrictions may dictate modular installation, which implies wet connectors.

Connectors also offer the option to modify, relocate, or extend seafloor systems without recovery or even disturbance of existing units. Examples here would be the expansion of an underwater range, addition of new wet-end elements to existing seafloor cable systems, or extension of the CEL's CMS test facility to a deeper site. This feature is also very useful in straightening or adjusting the precise configuration of newly laid cable because it is not likely that simple re-tensioning from the surface will be effective (Ref 9). Connectors are also very useful for interfacing a suspended cable structure with a bottom-laid service trunk because anchor positioning for the suspended systems can be critical and must not be impaired by handling the trunk line as well as the risers; entanglement becomes critical, and maneuverability is reduced.

Maintenance/Repair

Deep water repair of cables would be greatly improved by using CEL-3 series connectors as shown in the scenario of Figure 14. The total number of discrete insertions is the same (one connector, one splice) or, at worst, one greater (one connector and two splices). The ships and vehicles used would be the same as presently planned for repair of deep or buried cables (SCARAB system). The advantage of this system is that little or no slack is added to the cable. This means the result is electrically superior because a deep water repair typically adds 1 to 2 miles of slack (5% to 10% of section length), while insertion of a connector is equivalent to adding, at most, about 0.2 mile of cable (1% of section length). In addition to this factor of 5% to 10% reduction in added electrical attenuation, the removal of slack reduces problems in protecting the repaired cable against future damage.



(c) With connectors in position for mating by submersible/tethered vehicle.

Figure 14. Lowering technique for repair of SD cable with CEL-3 series connectors.

This scenario is presently under study by Teleglobe Canada, the Canadian telecommunication company. They are also having the CEL-3B connector design modified for compatibility with their 1.47 LW cable. The 1.47 LW is similar to SD cable but has a 54-ohm impedance and an aluminum outer conductor.

Support Vehicles

With some minor adjustments in the size of grip areas the CEL-3 series can be mated by any existing vehicle that has two or more manipulators. This includes even the fairly crude grabbers used for holding vehicles in place since only one half really needs to be controlled to achieve the needed relative motion. A few of the systems that can operate the connectors (Ref 10) are listed as follows:

Manned Vehicles	Unmanned Vehicles
SEACLIFF	SCARAB
TURTLE	RUWS
ALUMINAUT	CURV II and III (with work systems package)
BEAVER	
DEEP QUEST	
PC 1201	
PC 1202	
PC 1203	
PC 1204	
PISCES (Series)	

Design Options

For many SD cable applications, insulation of the outer conductor from seawater is not required; a simple lap seal over the contacts may suffice to prevent corrosion. If so, the connector diameter may be reduced about 1 inch, and the venting reservoir in the male half may be eliminated. If one then combines the reduced 1-inch outer conductor diameter of CEL-3 with the outside spring design of the CEL-3A Mod 1 shuttle piston, stacks the CEL-3B latch collar groove on top of the latches, and adds the shortened CEL cable termination, a much smaller, simpler, and cheaper version of the CEL-3B (designated CEL-3C) will result. This is shown in Figure 15. CEL-3C would be the recommended concept for any basic SD cable application.

To illustrate the flexibility of the CEL-3 concept, Figure 16 shows a coaxial wet connector for a smaller coaxial cable of the type often used on underwater ranges - the NUWES Keyport 15215 cable. The connector is 3 inches in diameter and 18 inches long.

These designs are just samples of the type of units that may be used in advancing systems toward truly underwater operation, with efficient cost-effective designs and without the risk and expense of operations at the air-sea interface.

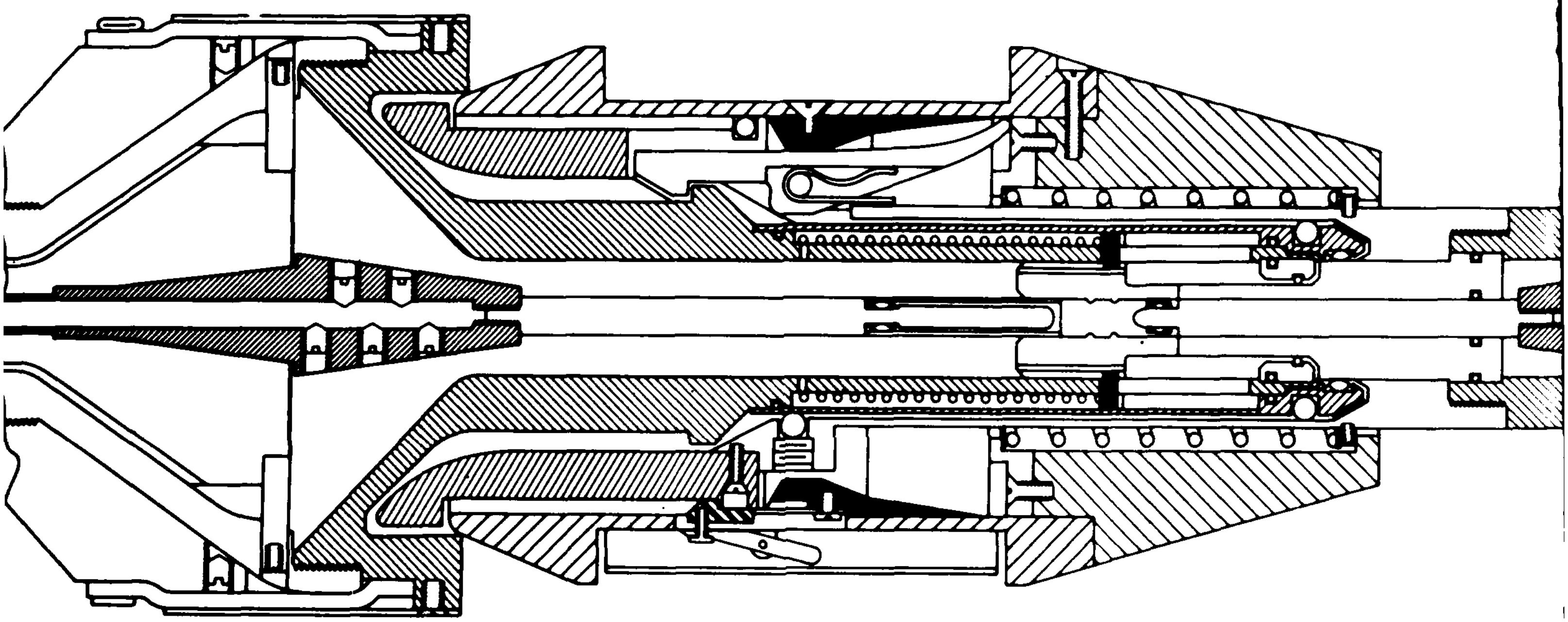
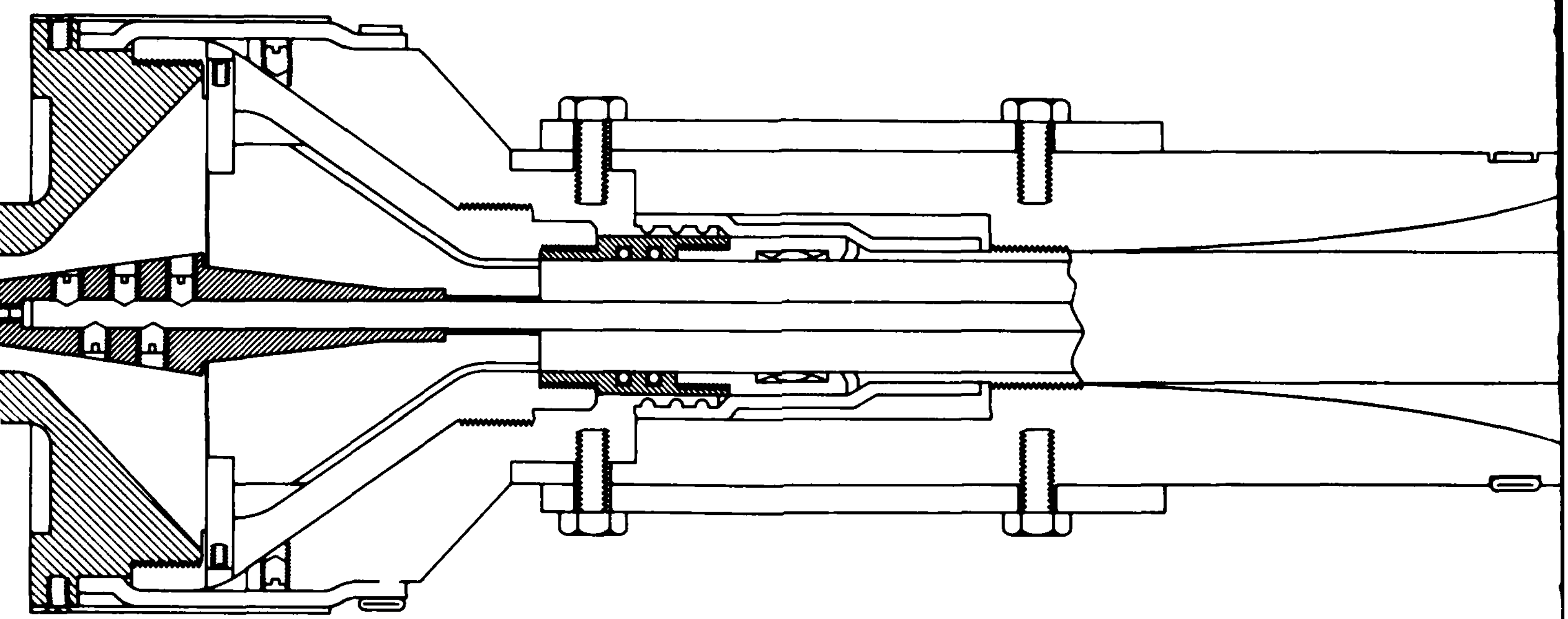


Figure 15. CEL-3C with f

Figure 15 (FOLDOUT)



ı field installable termination (concept).

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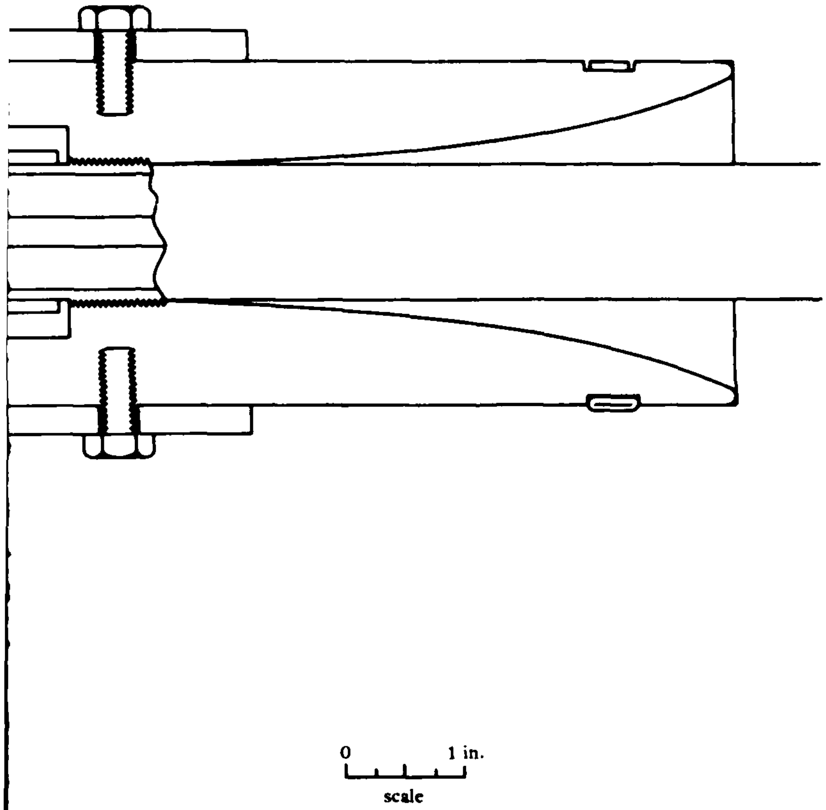
Figure 15 (FOLDOUT)



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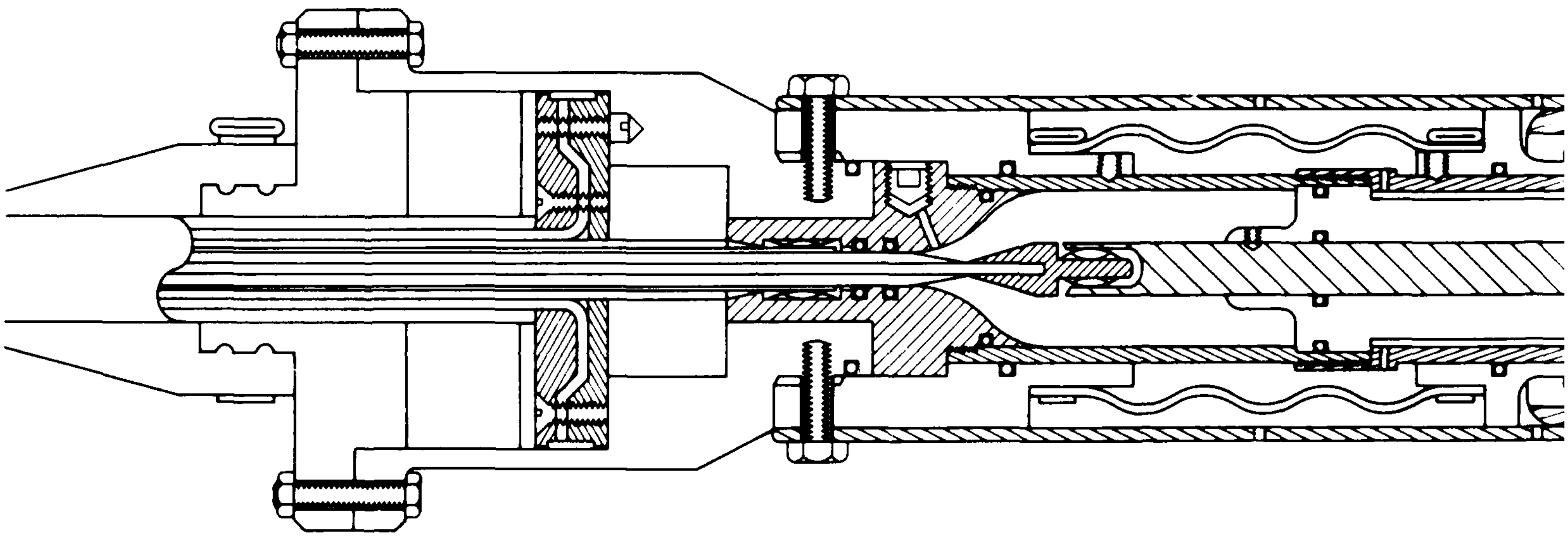
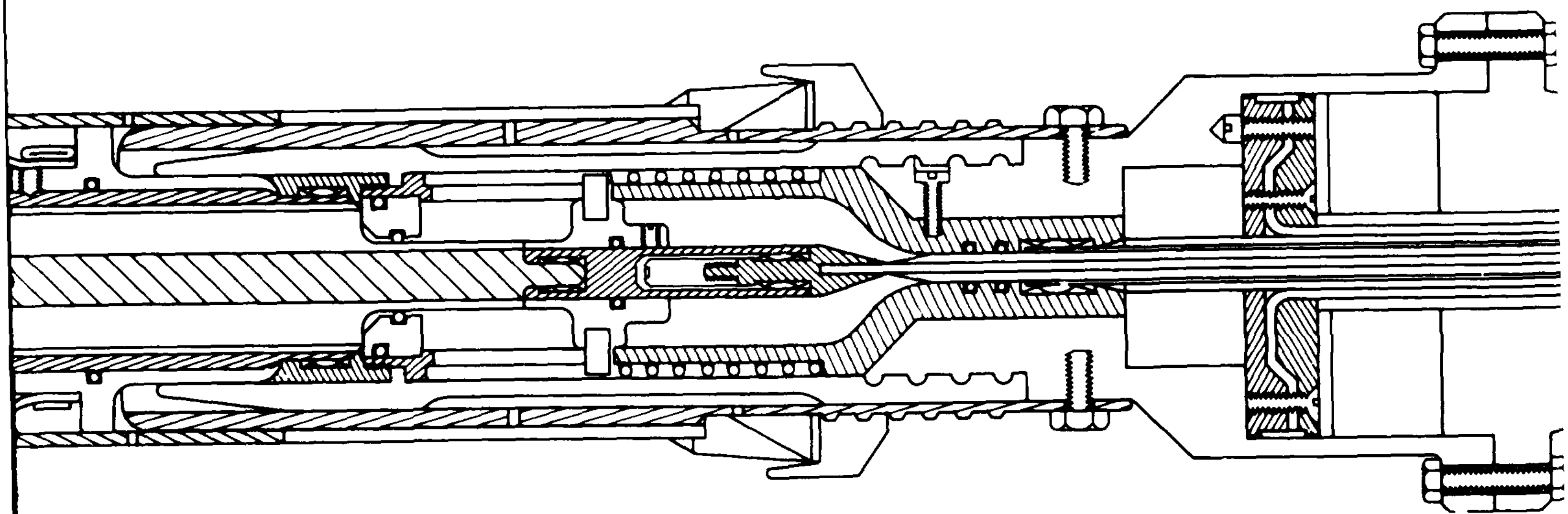


Figure 16. Coaxial wet connector for NUW

Figure 16



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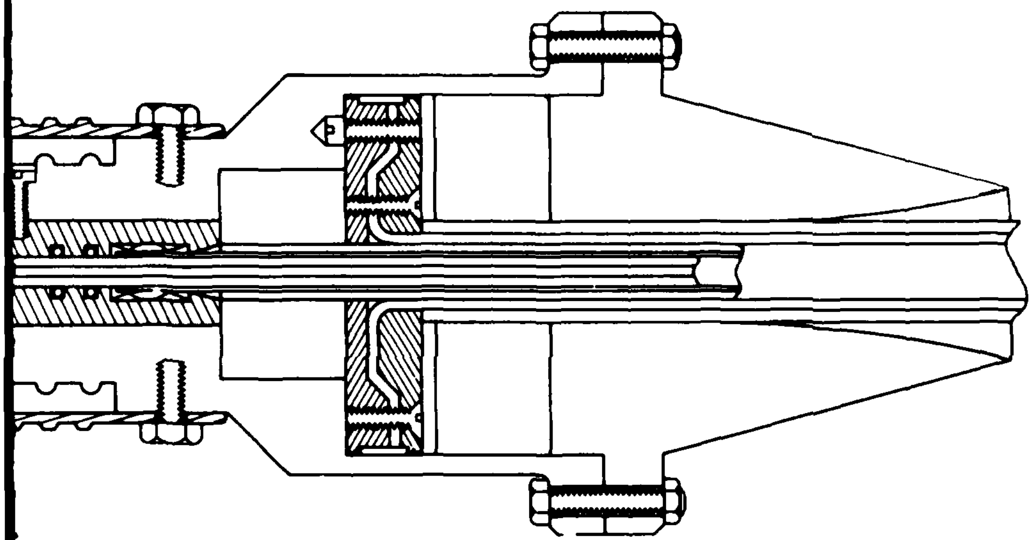
ector for NUWES Keyport coax cable (cable drawing 15215) (concept).

2

Figure 16 (FOLDOUT)



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SUMMARY AND CONCLUSIONS

An underwater-mateable coaxial connector for SD list 1 cable has been developed during the past 4 years at CEL as part of the Deep Ocean Technology Program. The performance requirements for the connector were derived from the cable specifications and vehicle/handling interface constraints. The CEL-3 series design is oil-filled and pressure-compensated, is fully coaxial throughout, is impedance-matched to the SD cable (44 ohms), operates at more than full cable voltage (±6,000 volts DC), carries the full cable breaking strength, is compatible with both manipulators and divers, is depth-unlimited, and is compatible with 10- to 20-year life requirements.

Four complete units and several subsystem mockups have been built and thoroughly laboratory-tested. Limited field testing and at-sea demonstrations have also been conducted, culminating in a 2-year, 6,000-foot demonstration of the CEL-3B prototype. A total of 229 recorded matings (72 of which were wet) were conducted on the various models. After minor modifications and debugging, the prototype CEL-3B met all performance requirements, including an impedance match to within 2%, 6,000-volt DC operation, pressure testing and wet mating to 5,500 psig, mating by submersible, unmating under tension of 10,000 pounds, and sustained submergence without degradation.

Coaxial wet connectors are now a viable design option for a variety of seafloor structure and other deep ocean applications, including installation of new systems, test and operation of installed systems, and maintenance, repair, and expansion or retrofit of such systems.

Test results show that the CEL-3B, as built, can operate at 12,000 volts DC, carry over 100 amperes, and remain impedance-matched to within 2% at 44 ohms at the upper frequency range of SD cable. The connector is coaxial throughout.

The CEL-3B has been successfully tested to 10,000 pounds of tension (the upper working limit on SD cable) and will unmate at this tension with an unmating force of approximately 600 pounds without damaging the connector.

In the test program a wide variety of design options has been considered for the basic concept, and the experience can be used, therefore, to tailor a design to many potential applications, both with SD cable and with other coaxial cable systems. Actual application will require a final design and any special testing required to obtain reliability data or other special information relevant to a particular application.

The variety of designs tested provides a basis for extending the CEL-3 series concept to a wide range of applications, from deep ocean cable repair to modular assembly of advanced ocean cable structures.

ACKNOWLEDGMENTS

The author wishes to thank Mr. William Greenert (NAVMAT Deep Ocean Technology Program) and Mr. Pat Cave (NAVFAC Code 03) for their steady support of wet connector technology over the past years.

Special thanks also are extended to the staff of CELMARK Engineering, Inc. for their imagination and quick response in solving the major mechanical problems of the CEL-3A concept to produce the smooth functioning of the CEL-3B prototype. Thanks also to Mr. Fred Potter of CEL for his patience with the oil spills, skinned knuckles, and general nervousness of working with high voltage as he labored with the author through the hardware development.

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Appendix A

PRINCIPLES OF UNDERWATER MATEABLE (WET) CONNECTORS

BACKGROUND

A wet connector is an end fitting for electrical or electromechanical cable that is capable of being mated or unmated underwater while still providing a desired level of electrical insulation for one or more conductors. There have been efforts to build such devices for at least the past 20 years. Literally dozens of designs are available, very few of which have actually been produced commercially in profitable quantities. The available hardware, however, is still very crude even when compared with the sister designs for dry-mateable underwater connectors. Mating forces are generally high, reliability is low, voltages are limited to signal and low power levels (about 600 volts maximum). In general, the full catalog of design and configuration options that exists for other types of connectors is just not available.

The need for wet connectors persists, however, and is growing. The Navy could significantly reduce maintenance costs and down time if many of its sonar systems could be replaced or repaired without dry-docking the ships. Many seafloor structures require wet connectors for installation and maintenance. The offshore oil industry finds more and more need for good connectors as operations move deeper and diving operations expand. The development of the coaxial wet connector discussed in this report was intended not only to meet a predicted specialized need of the Navy but also to help push forward technology and to stimulate further development in wet connectors in general.

The CEL-3 coaxial wet connector represents a rather sophisticated combination of wet connector principles and was designed to meet an unusually complicated and stringent set of requirements for a special application. It has evolved from a lengthy history of wet connector designs (outlined in Table A-1).

WET CONNECTOR CONCEPTS

For this discussion wet connectors are classified according to the method by which they provide an insulated path between the conductors and the adjacent conductors or surrounding environment. Each succeeding class has certain inherent advantages, as well as certain limitations. A knowledge and understanding of these principles is essential in the design, selection, or use of wet connectors (Figure A-1).

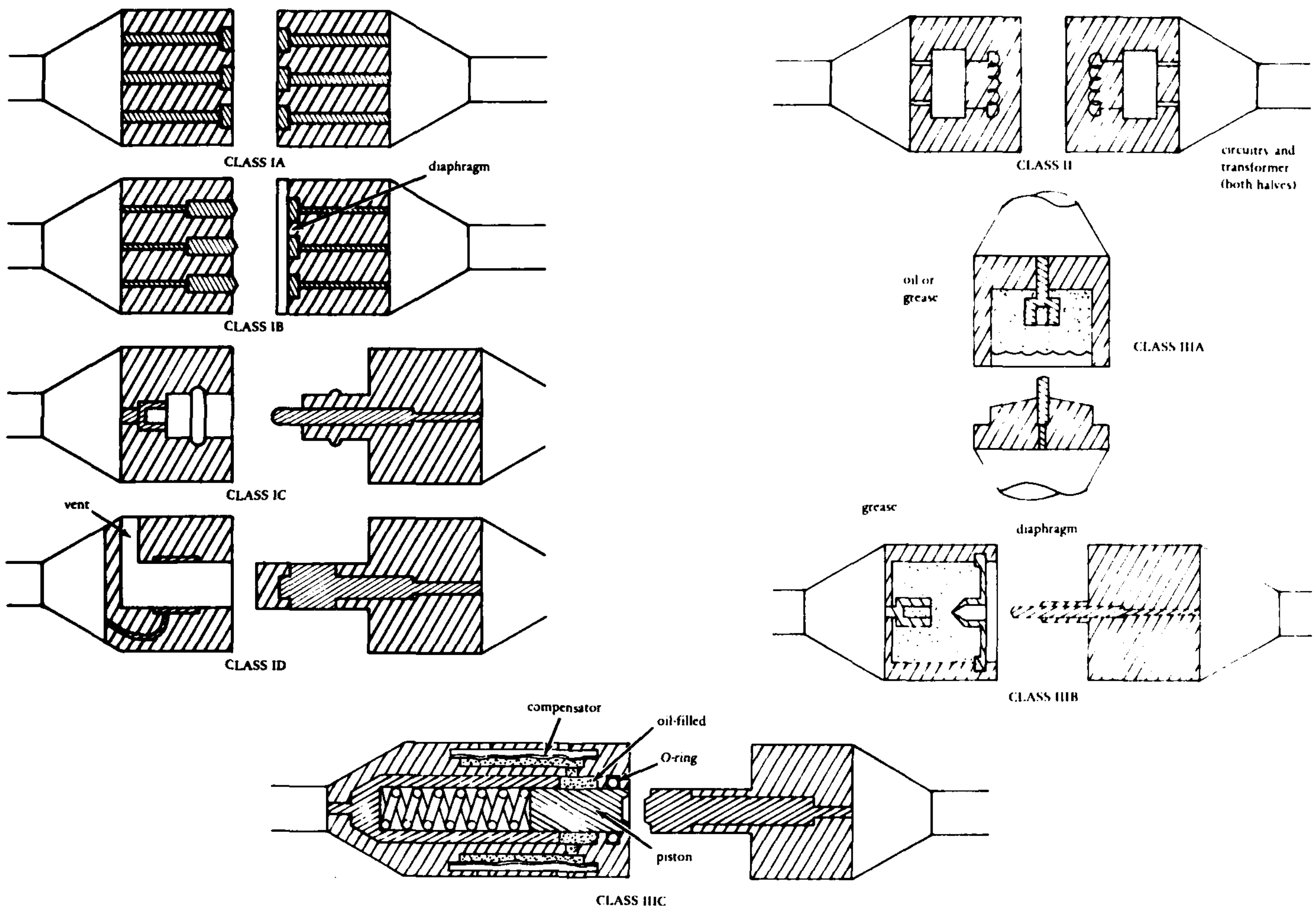

Figure A-1. Wet connector concepts.

Table A-1. Historical Summary of Wet Connector Designs

Patent No.	Inventor	Date	Description
Class IA (Direct Pressure Rubber/Rubber)			
3,478,297	Gimpel	11 Nov 1969	Flat face-to-face with pressure
3,478,298	Nelson	11 Nov 1969	Convex face
3,497,864	Barnet	24 Feb 1970	Tapered gland
3,537,062	Niskin	27 Oct 1970	Interlocking, self purging, but with one face still direct pressure
3,665,509	Elkins	23 May 1972	Conical, with a vacuum seal
3,693,133	Harbonn	19 Sep 1972	Flat face-to-face
3,731,258	Spicer	1 May 1973	Convex face
Commercial: None known. Government: None known.			
Class IB (Diaphragm Puncture)			
2,700,141	Jones	18 Jan 1955	Double diaphragm puncture with sealing compound
3,158,420	Olson	24 Nov 1964	Diaphragm puncture with self-riveting contacts
3,848,949	Falkner	19 Nov 1974	Diaphragm puncture with button contact
Commercial: Falkner patent in use by Deep Oil Technology, Long Beach, Calif. Government: None known.			
Class IC (Pin and Socket)			
2,935,720	Lorimer	3 May 1960	Cylindrical insert
3,124,405	Massa	10 Mar 1964	Held together by split ring
3,249,907	Hewitson	3 May 1966	Slightly tapered plus compression
3,344,391	Ruete	26 Sep 1967	Field-installable, claiming reduction in corona
3,350,677	Daum	31 Oct 1967	Basic IC unit, no detent

(continued)

Table A-1. Continued

Patent No.	Inventor	Date	Description
3,546,657	Cook	8 Dec 1970	Spot contacts on pin, leading shoulder
3,658,004	Kerr	15 Aug 1972	Deforming pin for pressure relief of basic unit
3,725,846	Strain	3 Apr 1973	Tapered seal, for corona reduction
3,787,796	Barr	22 Jan 1974	Raised shoulders on pin insulation
3,874,761	Stauffer	1 Apr 1975	Female insulation rolls back to reduce mating force
Commercial:	The most commonly used design class. A wide variety of manufacturers, including Brantner, Celmark, Deutsch, Glenair, ITT Cannon, Joy, Kintec, Massa, Souriau, Vector, and Viking. Full details are available from manufacturers. Although thousands of these units are in use in marine systems, they are almost never actually mated underwater.		
Government:	Many government agencies and ships use these connectors when mated dry. CEL is testing units for possible application to wet replacement of sonar transducer systems. The basic design class is incorporated in the outer conductor seal for the coaxial wet connector described in this report.		
Class ID (Pin and Socket, Vented)			
3,271,727	Nelson	6 Sep 1966	Basic ID design (EO)
3,277,424	Nelson	4 Oct 1966	Continues 3,271,727
3,368,181	Gimpel	6 Feb 1968	Contact for ID type
3,397,378	Dietrich	13 Aug 1968	Junction box version of EO
3,524,160	Robinson	11 Aug 1970	Vented shuttle pistons
3,626,356	Trammell	7 Dec 1971	Vented, button contacts, threaded shells for mating
3,641,479	O'Brien	8 Feb 1972	Vented, with replaceable O-ring seals
3,757,274	Hazelhurst	4 Sep 1973	Offset pin/socket for retaining force

(continued)

Table A-1. Continued

<table>
<tr><th>Patent No.</th><th>Inventor</th><th>Date</th><th>Description</th></tr>
<tr><td>3,832,673</td><td>Florian</td><td>27 Aug 1974</td><td>Ball contacts</td></tr>
<tr><td>Commercial:</td><td colspan="3">Electro (formerly ElectroOceanics) is prime manufacturer. Also Advanced Cable Assembly and Souriau make models with vents back through the male pin instead of out back of the female socket. These EO models are the only ones normally used for wet mating, such as on diver equipment or in some oil-filled applications. Most use, however, is in moist environments such as mining and on offshore structures.</td></tr>
<tr><td>Government:</td><td colspan="3">In use on some submersibles and on many reserach and development structures. Commercial items not a candidate for fleet use, although disclosures for improvements in the concept have been filed (Navy Case 62,759 Feb 1978, Wilson).</td></tr>
<tr><td colspan="4">Class II (Inductive)</td></tr>
<tr><td>None found</td><td></td><td></td><td></td></tr>
<tr><td>Commercial:</td><td colspan="3">Resource Instruments, Ltd., of Canada. Some proprietary split transformers used on seafloor; well completion units by GE/VETCO, TRW, Westinghouse.</td></tr>
<tr><td>Government:</td><td colspan="3">Some commercial units in use at CEL.</td></tr>
<tr><td colspan="4">Class IIIA (Free Fluid Dielectrics)</td></tr>
<tr><td>3,714,384</td><td>Burkhardt</td><td>30 Jan 1973</td><td>Inverted cylinder, oil-filled</td></tr>
<tr><td>Commercial:</td><td colspan="3">EXEECO Ltd. in use on offshore oil structures.</td></tr>
<tr><td>Government:</td><td colspan="3">Grease-filled coaxial cable splice under development at CEL (Ref 6). Grease-filled single wire splice used under water (CEL 1972-1974).</td></tr>
<tr><td colspan="4">Class IIIB (Grease-Filled or Oil-Filled, with Diaphragm)</td></tr>
<tr><td>3,972,581</td><td>Oldham</td><td>3 Aug 1976</td><td>Basic IIIB design</td></tr>
<tr><td>3,643,207</td><td>Viking</td><td>Feb 1972</td><td>Oil-filled with flat contacts</td></tr>
<tr><td>Commercial:</td><td colspan="3">Standard item available from STC (ITT), London, and Viking Industries.</td></tr>
<tr><td>Government:</td><td colspan="3">Principle in use in developmental underwater cable splice.</td></tr>
</table>

(continued)

Table A-1. Continued

Patent No.	Inventor	Date	Description
Class IIIC (Oil-Filled, Piston-Wiping)			
3,508,188	Buck	21 Apr 1970	Pressure-balanced, oil-filled (PBOF), both halves, with dummy pistons in female and sealed; ganged; movable pins in male
3,729,699	Briggs	24 Apr 1973	PBOF female only, with fixed male pins
3,821,690	Small	28 Jun 1974	PBOF both sides, with exchanging pins
3,845,450	Cole	29 Oct 1974	PBOF both sides, with same as Buck except cable is compensator
4,039,242	Wilson	2 Aug 1977	PBOF female only, coaxial, with shuttle piston and squeeze-ring actuation
Commercial:	No stock items, but developmental items available from Bendix, Celmark, Southwest Research Institute, Crouse-Hinds. A prototype high voltage version is being developed by Exxon Production Research, and the coaxial model is being developed by Teleglobe Canada.		
Government:	CEL has developed the fixed-pin version for use as battery-charging umbilical connectors for DSRV and battery box connectors for TRIESTE II (see Ref 1). The coaxial version has been used at CEL for installation of a seafloor test facility as described in this report. A disclosure has been filed (Navy Case 62,756, Wilson, Feb 1978) covering the simplified coaxial version of the device, including spring return of the shuttle piston and venting of the seal spaces in the coaxial void between halves.		

Class I - Rubber-to-Rubber Seals

Rubber-to-rubber seals are the simplest of the designs and usually are the cheapest and most rugged, while providing the basic functions of a connector – repeated wet mating. They are all limited in terms of voltage because the basic insulation is provided by the sealing of an elastomer against either a rigid or elastomeric surface. The length of the seal determines the voltage limitation and the mating force requirement. This class is generally limited to noncoaxial designs because of pressure-balance problems with the semirigid dielectric seals.

A rubber-to-rubber seal must be pressurized to work, and must also be clean and uniform. The fluid remaining on the surfaces can be minimized by lubricating the surface with a nonwetting substance such as silicone, by designing the surfaces so that they squeegee the water out as they are pressed together, or by using interference fits for a wiping action. Once an insulating seal begins to break down, either because of excessive voltage or because of water leakage, leakage current is channeled in a very concentrated line, which usually causes heat and breakdown of the rubber. This action leaves a carbon path which is not self-healing and is usually not even repairable.

In contrast a fluid dielectric can be designed to wet insulation surfaces preferentially, to absorb (or at least isolate) seawater leakage, and to flow back in to re-establish insulation even after a breakdown has occurred.

<u>Class IA (Direct Pressure Face Seal)</u>. Mechanically, this is the simplest type of wet connector. The electrical contacts are simply molded into two opposing rubber faces which are then pressed tightly together, reducing the water on the insulating surfaces to a very thin film. The rule is: the greater the separation between contacts and the higher the mating pressure, the better the insulation resistance. Variations on the theme include making the surfaces convex for better wiping action or making them conical for ease of alignment and as a mating force amplifier. In this case the faces are never dead-face, and the contacts are not wiped before mating. An added mechanical device is required to obtain the needed pressure for electrical contact and insulating seals - all of which are in parallel and, therefore, additive. The design is generally insensitive to pressure but sensitive to contamination on the mating faces. It can be made very tolerant of lateral misalignment.

<u>Class IB (Diaphragm Puncture)</u>. The earliest design for a wet connector was patented in 1955. In this device, both sides were dead-face when unmated. The two halves were first latched together mechanically and then a set of pins were pushed through two sets of diaphragms, each of which had a sealing compound between them. The device was only as good as the ability of the two connector halves to be forced together and water squeezed off the mating faces. The diaphragm puncture action does cause localized high pressure right around the contacts so it provides a slight improvement over the basic face-to-face seal but only at the expense of a limited number of matings because the diaphragms are damaged with each mating.

The other patented diaphragm design is presently in use by Deep Oil Technology, Long Beach, Calif., and incorporates a heavy shell so divers can lock the halves together with wrenches to get high forces on the rubber seals. This device has been successfully used to 440 volts AC with several matings over a period of years.

Class IC (Pin and Socket). In the pin and socket design, the force is applied to the insulating rubber surfaces by interference fit of cylindrical surfaces. This seal is usually formed by molded rubber surfaces - sometimes with a detent or raised portion included, sometimes with one surface an elastomer and the other rigid dielectric. In all cases, in the pin and socket class the outer cylindrical portion of the seal must be sufficiently compliant to allow the seal to open so fluid trapped inside can be vented during mating. During unmating, the seal must be artificially opened prior to separation of the connectors, or the force caused by the differential between ambient pressure and that inside the connector acting on the pins must be overcome directly. The contacts are not wiped during mating, and seawater does remain in the electrical contact area after mating - although the area is isolated from the external environment. Limited corrosion can occur. Maintenance of these units is important - but difficult. The recessed nature of the socket contact makes it difficult to remove any salt crystals or dirt so contacts may be damaged during repeated matings. If contact resistance becomes high, the closed nature of the design causes problems because the seawater inside can be heated sufficiently in power conductors to cause steam and catastrophic failure of the unit. In many connector designs not intended for wet mating a small seal of this type is provided around the base of each contact as a secondary seal to reduce pin damage and retard failure in case the primary connector shell seal leaks.

Performance of this class is significantly improved if it is well-lubricated. It can begin to look like a Class IIIA design, especially for a limited number of matings. Cleaning and lubrication of this type are recommended before each mating, whether wet or dry.

This class is never dead-face but can be explosion-proof (sealed until after electrical contact is broken).

Class ID (Pin and Socket, Vented). The addition of a pressure-balancing vent to each socket (or back through each pin) is the feature that makes this the first wet connector class that is conceptually fully adapted to the ocean environment. The various designs use variations on the contact type and locate the vent in different positions, but all are essentially smooth-bore sockets with pins of uniform diameter to prevent any pistoning action (pressure differential). Mating forces are thus just the sum of the frictional forces caused by the interference fit of seals and contacts. In practice, however, this can be quite large for multiple contact connectors. The best designs utilize the more advanced electrical contacts with some sort of louvered band or spring between two continuous cylindrical shells. This greatly reduces the basic mating force and prevents the outer contact ring from being differentially compressed onto the rigid pin contact when pressure increases. No commercially available device includes these features yet. Using continuous electrical shells also reduces mold flashing in the socket and greatly improves quality assurance.

Like the Class IC, this system also benefits from lubrication but is much less vulnerable to contamination because the contact itself is wiped and the vent allows debris to be pushed out during mating. Its weakness is that each contact has at least twice the insulating seal area of a corresponding Class IC design because insulation is on both the front and back of each contact ring.

In both Class IC and ID designs, concentric cylindrical pin and socket arrangements for the contacts provide better packaging density and fundamentally better reliability (less leakage area) than do spot contacts of equivalent size.

Class II - Inductive

Although the inductive coupler has some internal electrical limitations, its compatibility with the ocean environment is nearly absolute: (1) electrical contacts are never exposed to the environment, (2) the device has no moving parts, (3) the mating force is essentially zero, (4) the connector is insensitive to contamination and less sensitive to alignment than most others, (5) it almost never wears out, and (6) it is explosion-proof.

The main limitation is that it is not possible to have many fully isolated circuits through the connector without multiplexing equipment in the system. The device is also very inefficient in size when carrying more than a few watts of power or high voltages.

These devices have been produced commercially and are gaining acceptance in many applications.

Class III - Fluid Dielectrics

In Class III connectors the contacts are immersed in a fluid dielectric such as oil or grease when mated. They may or may not have some sort of preliminary wiping seal or containment mechanism for the fluid. These designs offer the best known type of insulation because the fluids are highly resistant to corona and can be void-free. In addition, the connectors are easily pressure-compensated, can preferentially wet surfaces to absorb or displace seawater so that contacts have essentially unlimited life, are leak-tolerant, and greatly ease manufacturing tolerances on most molded parts. If occasional overvoltage does cause breakdown, the dielectric is self-healing.

In practical designs, these connectors are somewhat more complicated mechanically than those of other classes and are usually more expensive to manufacture. What litte maintenance they require is easy, however, and they offer a great deal more capability than other wet connector classes. In situations requiring the Class III features, the added cost or complexity is usually easily justified.

Class IIIA (Free-Fluid Dielectrics). Any connector can be a Class IIIA connector if an inverted bucket is filled with oil and the connectors are held up in the bucket during mating or if the connectors are completely filled with a grease before mating, either before immersion or while under water. These types are mechanically messy but electrically sound. They have all the advantages of a fluid dielectric once mated, and repeated mating is possible with refurbishment of the dielectric reservoir. For a one-time, high-quality connection this system would be very suitable. EXEECO, Ltd. sells a IIIA connector used in offshore oil applications.

Class IIIB (Fluid-Filled with Diaphragm). The addition of a diaphragm which is either punctured directly or has pre-formed holes or flaps for contact entry greatly increases the utility of the grease-filled connector beyond the basic IIIA design. The system is still rather simple and rugged but its performance goes considerably beyond the nearest competitor, the Class ID vented rubber design.

A commercial connector of this class is produced by Standard Telephones and Cables, Ltd., of England. In this version the membrane over the grease-filled female half has holes molded nearly through the membrane in line with each socket contact, with the inside of each hole just closed off by a thin flap which is cross-hatched to split open easily but which still acts to retain grease and keeps out loose contaminants when the connector is unmated. During mating, the male pin is wiped off by a slight interference fit with the hole in the membrane and then by the grease inside. The membrane flexes outward during mating to accommodate the increase in internal volume during the entry of the male pins and at all times acts as a compensator for the grease-filled space. This leads to very low mating forces (just the small force of a well-lubricated wiping membrane and the actual electrical contacts), which are insensitive to depth. The contacts and insulating surfaces of the male pin are well-wiped during mating, and the female contacts never touch seawater. In general, the female will be dead-face until mated.

A small oil-filled version is available from Viking Industries. It adds the feature of rigidly supported flat slits in the diaphragm.

The Class IIIB design is somewhat limited in pin size to signal/low-power applications, and does not have the complexity of moving parts of the larger IIIC oil-filled designs. The voltage rating is easily made much higher than is possible with rubber-seal systems (1,000-5,000 volts is practical) although, again, it is likely to be inferior to IIIC oil-filled designs at very high voltage ratings (above 5,000 volts). The fact that the wiping seal is not particularly stringent means that this class of connector would likely carry in more contamination per mating and be degraded more by a given contamination than would the IIIC oil-filled systems. Maintenance would be required after the first few matings. Fortunately, this only means recharging or, at most, replacing the fluid – an easy operation if access to the device is provided. Grease can even be recharged underwater if desired.

Another application of the fluid-filled diaphragm is the underwater splice presently under development at CEL. In this system, the insulation on the male pin is much thicker so the membrane wiping is not as effective and the large male pin volume makes simple membrane movement inadequate for compensating the volume change during mating. In this design, the membrane therefore has vent holes with small check-valve flaps to allow grease to flow out as the cable is inserted into the splice. Since the splice is, in effect, a one-time mating connector, the irreversibility of flow is acceptable.

The IIIB design nicely fills the performance gap between the rubber molded systems and the larger IIIC oil-filled systems.

Class IIIC (Oil-Filled). Class IIIC has many variations but its central premise is that the leakge path should be flooded by a liquid dielectric and sealed by a pressure-balanced wiping seal (an O-ring). The O-ring allows large pin size but requires a dummy piston to prevent fluid loss when unmated. This provides essentially unlimited voltage potential (sea tests to 6,000 volts DC with laboratory tests to 35,000 volts DC), improved cooling to allow high current (to 2,000 amperes so far), and repeated mating with no maintenance. An additional feature is that of having one or both halves of the connector dead-face so that the leads may be energized during mating. The design has been shown to be explosion-proof for up to 120 amperes. It is also adaptable to multi-pin applications, coaxial configurations, and special designs requiring use of the compensating fluid to provide hydraulic disconnect capability for easy operation by manipulator. Models of Class IIIC have been built to handle up to 10 MW through a single pin, and similar versions are being installed on the DSRV and TRIESTE II for use in the battery-power leads.

More details on IIIC connectors are available in CEL reports and the patents referenced. The Class IIIC is the most versatile, most capable wet connector design but is also, usually, the most expensive and complicated. At present there have been no applications requiring IIIC connectors in quantity; but, with the development of the CEL coaxial connector, the Canadian telecommunications company, Teleglobe Canada, is adapting them for use in cable repair. Exxon Production Research has also developed a 35-kV version for seafloor wellhead/ pumping station applications. Diver safety requirements are also prompting use of this connector class in shallow underwater range operations.

Appendix B

CEL-3B MAJOR PARTS LIST AND MATERIALS

Note: Part numbers are referenced to fabrication drawings CELMARK X-250-67&71.

Part No.	No. in Figure 4	Name	Material
X-250-13	1	Ring, contact	Be-Cu 33-24 (plated w/ 0.0002 minimum gold)
X-250-9	2	Screw	Brass, bright dip
X-250-19	3, 15	Center conductor	Brass
X-250-15	4	Couple, male	Be-Cu 32-35 (plated w/ 0.0002 minimum gold)
X-250-14	5	O-ring	Buna "N"
X-250-36	6	Bellows, compensator	Buna "N"
X-250-6	7, 21	Shell, female	6 Al 4VTi
X-250-8	8, 24	Shell, male	6 Al 4VTi
X-250-2	9	Latch	6 Al 4VTi
X-250-5	10	Sleeve, slider	Acetal copolymer (Delrin)
-	11	Detent	6 Al 4VTi
X-250-4	12	Funnel	Acetal copolymer (Delrin)
X-250-31	13	Conductor, inner male	Hard brass (0.0002 minimum gold)
1-009-0006-000	14	Boot	Nitrile rubber
X-250-46	16	Tubing shrink	Raychem thermofit (WCSF-250)
X-250-4	17	Strain relief	Acetal copolymer (Delrin)
X-250-22	18	Pin, spring center	Acetal copolymer (Delrin)

(continued)

Part No.	No. in Figure 4	Name	Material
X-250-32	19	Conductor, inner female	Hard-drawn brass (0.00005 minimum gold)
X-250-27	20	Seal ring	Cast acrylic
X-250-50	22	Spring, sleeve	302 SS QQ-W-763 (passivate)
X-250-37	23	Spring, latch	"Pure" titanium (Type 2)
-	25	Detent cover plate	6 Al 4VTi
-	27	Stops	Delrin
-	-	Fluid dielectric	White mineral oil (USP)
X-250-43	28	Ball bearings	Acetal copolymer (Delrin)

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