High Voltage Testing of an ROV Electro-Optical Tether Cable

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Abstract **- Insulation life testing of an ROV tether cable was recently performed by MBARI and WHOI in cooperation with PCC and CTL. The testing was undertaken to determine whether higher cable operating voltages were possible for future ROV system designs and upgrades. The tests were performed on field-aged samples of 17.3 mm (0.68") steel armored electro-optical tow cable used in small, deep ROV systems such as MBARI's *Tiburon* and WHOI's *JASON*. The test results indicate that the cable is capable of long-term operation at higher voltages than presently used with these systems. Design work is now proceeding to incorporate this data into improvements in the power capacity of these vehicles. This paper reviews the basic architecture of ROV power transmission systems, discusses the factors affecting the insulation voltage stress, describes the cable test methods, and reports the results of the tests.**

I. INTRODUCTION

A. ROV Tether Cables

ROV (Remotely Operated Vehicle) systems universally employ tether cables to provide power to and communication with the vehicle. The operational performance of the vehicle is usually dominated by the mass, hydrodynamic drag, and electrical capacity of the cable, especially in the case of deep vehicle systems designed for working depths greater than 1,000 meters. For example, in MBARI's 4000 m rated Tiburon system [1], the vehicle mass of 3400 kg is outweighed by the cable mass of 4700 kg, and the vehicle frontal drag area of about 8 m^2 is dwarfed by the deployed cable drag area (diameter times length) of nearly 80 m^2. The situation with WHOI's *JASON* [2], a smaller (2800 kg) vehicle with a deeper (6000 m) rating and longer cable, is even more pronounced. The mass and drag of the cable has a major impact on the vehicle system's speed, maneuverability, and ability to work in adverse ocean currents, since the cable must follow all but small motions of the vehicle. Cable size and weight also influences important secondary factors such as the deck footprint of the handling system, shipping costs, and so on. Therefore, careful optimization of every aspect of the cable's design has major payoffs in overall system performance.

The diameter (drag) and weight of the tether cable for these ROV systems is principally influenced by the required electrical capacity and mechanical strength of the cable. Thanks to the advent of fiber-optic data communications, nearly unlimited data capacity now requires less than 5% of the cable cross-sectional area and just a few percent of the weight, although the optical fibers do still strongly influence allowable bending radius and cable handling practices. Mechanically, the principal requirement for the cable is that it support its own weight, while hanging full length vertically in the ocean, during the design maximum sea state for the system. (The vehicle does not significantly load the cable in most cases; it is neutrally buoyant, and its mass is isolated from the main vertical run of cable, for small motions at least, by either a floated S-section for *Tiburon* or a depressor weight and neutral cable section for *JASON*.) The principal "payload" that the cable must support is the electrical conductors. The conductor weight has a compound effect on the cable, contributing both its own weight plus the weight of the strength member required to support it. The conductor size (including insulation) contributes significantly to the overall diameter of the cable, as well. Only some future quantum leap in electrical transmission technology, comparable to the introduction of fiber optic waveguides, seems capable of affecting this state of affairs.

B. Cable Power Capacity

The electrical power transmission capacity of the cable affects the size and weight of the cable and its handling system, the drag of the deployed cable, and also the thrust power available at the vehicle. The cable power capacity is established during the vehicle system design process in a complex tradeoff between thrust, drag, speed, weight, and payload power requirements. Electrical power transmission per unit cable diameter is maximized by operating at the highest practical current and voltage levels, subject to allowable limits for temperature and voltage stress. For any given distance and power requirement, it can be shown [3] that there is an optimum current/voltage operating point that balances the copper and insulation contents in order to minimize overall cable diameter. It can further be shown that a related operating point will minimize overall cable weight.

The operating current of deep ROV tether cables has generally been limited by voltage drop due to their length, rather than by thermal limits due to insulation temperature. Since hard-drawn electrolytic copper has defined the state of the conductor art for decades (except for uneconomical alternatives such as oxygen-free copper and precious metals), little optimization of conductor resistance, and thus of operating current density, has been possible for ROV system designers.

The operating voltage of ROV cables has generally been limited by the allowable voltage stress in the cable insulation. In contrast to the conductor current density, the allowable voltage stress level is a quantity that is known less precisely, and is more subject to the effect of environmental variables upon the insulation. The voltage stress is a measure of the electric field gradient, in volts per meter or usually the more practical units kV/mm or V/mil (where 1 mil = 0.001 inches). This stress is a scalar field that varies throughout the cross section of the cable, is determined by cable geometry and the applied voltage, and is generally at a maximum directly adjacent to the conductor surfaces. Severe overstress may cause immediate insulation breakdown, while moderate overstress may cause gradual insulation degradation leading to eventual failure and shortened service life. The presence of moisture in direct contact with the cable insulation accelerates degradation and further shortens cable life. Below some threshold stress value that depends upon the insulation material and manufacturing process, the insulation will be unaffected and its service life will be determined by mechanical, environmental, or other factors. Since in rough terms the power transmission capacity of the cable increases as the square of the operating voltage, there is considerable motivation to "work" the cable insulation as hard as possible, consistent with a reasonable service life, in order to maximize power transmission to the vehicle and to minimize cable size.

The safe working voltage stress of extruded plastic insulation for power cables is a well-studied topic of considerable interest in the electric utility industry. Industry standards have been developed for design and operation of cables in this service [4], which typically spend their life in underground conduits or ducts and are expected to operate safely for 30-40 years or more. ROV cables, in contrast, are typically submerged in high pressure salt water, pulled repeatedly through sheaves, and subject to large load (strain) variations; they generally fulfill expectations if they survive for several thousand operating hours spread over a period of a few years. Due to these environmental contrasts, we felt it would be useful to perform a basic set of insulation life tests on a previously field-aged sample of ROV cable, which presumably had already been degraded by these conditions of service. Our goal was to determine whether margin exists to operate the cable at higher voltages in future ROV designs. As a target, a voltage increase of 75% was chosen, which would allow roughly a threefold increase in the power capacity of the cable.

II. CABLE CONSTRUCTION AND VOLTAGE STRESS

The electro-mechanical-optical cables used for Tiburon and JASON are similar in design, materials, and construction. The JASON cable (Fig. 1) was chosen for these tests since identical cables are in use aboard several UNOLS (University-National Oceanographic Laboratory System) research ships, and a field-aged sample was readily available. The JASON cable is manufactured by The Rochester Corporation (Culpeper, VA) as TRC A302351. The cable core consists of three metal-armored single-mode optical fibers and three #11 AWG (2.5 mm diameter; 4.2 mm^2) copper conductors insulated with 0.74 mm wall thickness extruded High Density Polyethylene (HDPE). The core is armored with three layers of steel wire in a rotation-balanced configuration, with a nominal overall outside diameter of 17.3 mm (0.68 inches). The Tiburon cable, TRC 03507, differs mainly in having #10 AWG (5.7 mm^2) conductors and two rather than three armor layers.

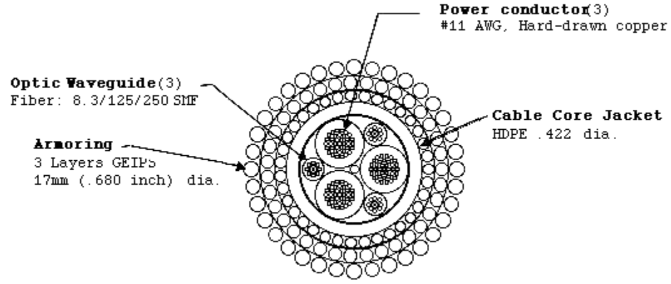

Fig. 1 Cross section of TRC A302351 cable (courtesy The Rochester Corporation)

The TRC A302351 cable core does not contain electric field control elements such as shielding or screening between the conductors, and in addition it contains metallic elements such as the optical fiber armor and a filler wire. These factors lead to a complex stress distribution within the conductor insulation, similar to that encountered in belted-construction utility cables. Although calculation of the exact stress values for this construction is quite involved, simplifying assumptions can yield an approximate value that is useful for comparison purposes, and also to illustrate the cable parameters that affect the voltage stress value. The simplest assumption, and one that might at some point occur in reality, is to assume the cable core flooded with conducting salt water. This reduces each conductor to an isolated coaxial cylinder with a single layer of insulation. A slightly more rigorous, though still over-simplified analysis, for example of parallel coaxial cylinders separated by two layers of insulation, will yield lower stress values than this simple conservative case.

The peak electric field stress for a single, coaxial, insulated conductor is given [5] by:

$$E_{pk} = \frac{2SV}{d\ln(D/d)} \quad (1)$$

where E is the electric field strength, V is the applied voltage, d is the conductor diameter, D is the diameter over the insulation, and S is an empirical "stranding factor", commonly taken as equal to 1.1 for the 37-strand conductors in these cables. As mentioned, the peak stress occurs at the surface of the inner conductor; the stranding factor accounts for the extra field stress caused by the smaller-diameter wire strands, compared with the case of a smooth, solid conductor. Utility practice, on larger, higher-voltage cables, is to smooth the conductor surface with a conducting material, and to apply a conducting screen or shield over the surface of each conductor's insulation. This makes the stress simple, radial, and uniform throughout the insulation, due to the enforcement of coaxial geometry.

The tether cable in both the *JASON* and *Tiburon* systems operates with three phase, 400 Hz AC power, at a maximum of 1000 V RMS line-to-neutral. Evaluating (1) at this voltage, using the dimensions for TRC A302351, yields an approximate RMS field strength of 1.9kV/mm (49 V/mil). A 75% increase in operating voltage, to 1750 V, would increase the nominal stress to 3.3 kV/mm (80 V/mil). A typical handbook value [6] for the short-term breakdown strength of HDPE is 20-22 kV/mm (500-550 V/mil) for temperatures below 75 C, which applies to ROV cable operation. Typical operating stress in utility practice is in the range of 2-2.5 kV/mm for medium voltage cables, and up to 4 kV/mm for high voltage (above 69 kV) cables with specialized insulation and carefully engineered electric field control. These practices are not directly applicable to the ROV cables however, since as noted the ROV cables lack well-defined fields and have different environmental conditions. Direct testing of actual cable is required in order to confidently predict the ability of these cables to handle a given set of operating conditions.

III. CABLE TEST METHODOLOGY

An array of tests is available to evaluate the condition of cable insulation and to predict its remaining life [7,8] under service conditions. Here we briefly summarize the three methods chosen for this study.

A. Physical Inspection

The most common symptom of long-term insulation degradation observed in polymeric-insulated cables is termed water-treeing. This phenomenon is caused by enhancement of voltage stresses at insulation impurities, voids, and protrusions, in the presence of moisture. The degradation is progressive in that the damage originates at a local point of high field stress and propagates over time until enough insulation is breached that a final breakdown takes place. Treeing is detected by dissecting a sample of aged cable that has been removed from service, sectioning thin cross-sectional slices of the insulation, and staining the slices with a dye that enhances microscopic observation, where any imperfections and trees can be observed. The damaged sites are easily viewed in translucent insulation, but very difficult to find in colored insulation. The degree of treeing observed by a trained operator is indicative of the degradation experienced by the cable insulation under the prior conditions of service. The absence of water trees is not an indication of high dielectric strength of the insulation. Water will diffuse into the insulation of all polymeric cables, lowering their breakdown strength, however water trees will only originate at the location of imperfections and lower dielectric strength. This examination provides a cost effective basic check on the health of a cable, and can indicate whether further testing is warranted to evaluate the effect of more severe operating conditions.

B. Breakdown Voltage

This is the most important and effective test to be performed on a length of cable. It will determine the weakest point in the insulation and when results are compared with similar test results obtained on the same cable when new, will provide an idea of the degradation experienced. Based on knowledge of the rate of degradation and the behavior of particular types of cable during aging, one can extrapolate to estimate the remaining life of a cable. During the test, cable samples are subjected to voltage stress for short periods in increasing increments until insulation breakdown occurs. This test checks a continuous length of cable for defects, rather than discrete sites as in the physical inspection. In our test program, this activity also afforded an opportunity to develop corona-free cable terminations that would be reliable at elevated testing voltages, and could be used in the third phase of testing.

C. Accelerated Aging

In order to evaluate the longer-term effects of high voltage stress, a set of cable samples are exposed to elevated voltage levels for extended periods. At the end of each period, a subset of the samples is subjected to a breakdown voltage test, to establish the progress of deterioration, if any. The exposure is then repeated on the remaining samples for another period, followed by a breakdown test on the next subset of samples, and so on until the test is complete. The time at elevated voltage can be converted, using methods described below, into equivalent time at the lower, normal voltage. The choice of test period, test voltage, test duration, and test conditions represents a compromise between cost and thoroughness. It should also be noted that the test only simulates a few of the great variety of cable stresses present during ROV operation. A field trial is the only method that can definitively establish the ability of the cable to operate in a given set of conditions.

IV. TESTS AND RESULTS

The tests described in Section II were performed on a section of TRC A302351 cable. The cable segment from which all test samples were taken was in service at the submerged or vehicle end of the *JASON* system cable from 1994 to 1999, accumulating 6700 hours of operation over 230 dives on 21 cruises. The cable was routinely washed and lubricated when in service. It was removed from service due to a broken armor wire 800 meters from the submerged end; the electro-optical core of the cable experienced zero defects or failures during its operational life. This cable segment was judged to have experienced a normal set of mechanical, environmental, and electrical stresses typical of deep ROV operation.

A. Physical Inspection

Dissection and visual evaluation of three cable samples was performed (Fig. 2). The results of the evaluation showed that the cable was very well constructed. The void-filling compound observed in all layers of the construction appeared to keep the moisture away from the two inner layers of armor wires, which did not show signs of rust or deterioration, and away from the cable core. The insulation from several cable samples was cut into thin wafers and evaluated microscopically (Fig. 3). No defects, treeing, contaminants, or voids were noted. Based upon these results, it was concluded that the cable construction effectively excludes water from the cable core, and that electrical testing for the higher operating voltage should be performed.

B. Breakdown Voltage Test Results

Two single insulated conductors were removed from a sample of cable and tested in water (as the outer conductor), to determine the quality of the individual phase conductors. Testing was performed at 60 Hz, with voltage increasing by 1 kV for each five minutes. After reaching 10 kV, the increase was 2 kV per step, and after reaching 20 kV, 4 kV per step. The two insulated conductors broke down at 24 kV and 28 kV, respectively. Several cable termination designs were then developed, and after actual application of the terminations, one method was selected for further breakdown testing of the complete cable (Fig. 4). The tests were performed at 60 Hz, on one phase conductor, with the other two conductors and all metallic elements -- filler wire, fiber optic armor, and main armor -- connected to ground. This cable sample failed with 12 kV applied after 29 minutes. The breakdown was to the armor of the optical fiber.

Fig. 2 Cable sample dissected for visual evaluation.

Fig. 3 Insulation sectioned and stained for voids, contaminants, and treeing inspection.

C. Accelerated Aging Test Results

The accelerated aging program was developed in order to establish the likelihood of cable survival, at 1750 V RMS line-to-ground, in a relatively short time. The program was based upon results from the Inspection and Breakdown tests, and upon the known operating conditions of the cable.

The testing was performed at room temperature, since the cable normally operates either in seawater or on a winch drum close to ambient temperature. The tests were performed using a three phase 60 Hz power supply. (The application of 60 Hz results to 400 Hz conditions is discussed below.) Tests were performed with the cable dry, since the physical inspection showed the jacket and void-filling compound to be effective in excluding water from the core of the cable. The fiber armor, filler wire, and cable armor were grounded during the tests.

The program was designed to require the minimum number of samples and voltage steps that would show the cable to be capable of operating at 1750 volts with acceptable confidence. The test program consisted of 15 cable samples and three 20-day test periods, during which the samples were subjected to progressively higher voltage stress levels. The voltage levels for the three aging test steps were the proposed operating voltage of 1750 V phase-to-ground, 2625 V (150% of operating voltage), and 4375 V (250% of operating voltage). At the conclusion of each period, insulation damage was assessed on five of the samples by performing an AC voltage breakdown test, and by subsequent dissection and visual inspection. The breakdown tests began at 5 kV and increased in 1 kV steps for each five-minute period.

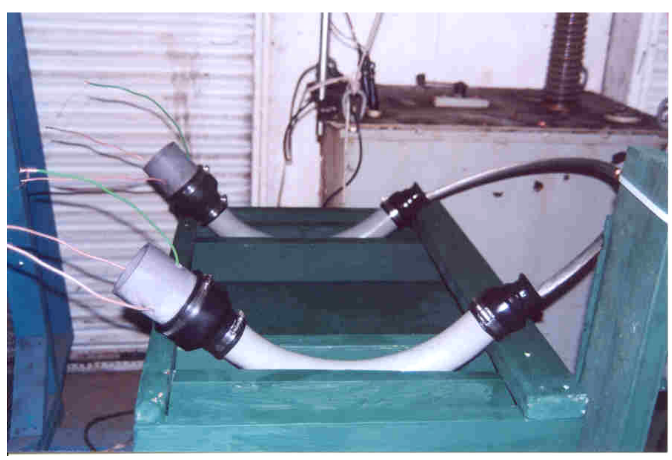

Fig. 4 Cable terminations undergoing breakdown test.

TABLE 1
BREAKDOWN VOLTAGE (kV)
(Field and Laboratory Aged Cable)

Sample	Tested After		
	20 days at 1750 V	20 days at 2625 V	20 days at 4375 V
1	12	12	13
2	13	13	14
3	14	13	15
4	14	14	15
5	15	15	15

The test results are shown in Table 1 above. None of the samples failed during the 20 day aging periods. During the breakdown tests, all failures occurred between one of the insulated conductors and the center filler wire in the cable.

These results are shown graphically in Figure 5, using the two-parameter Weibull function [9]. In this plot, Eta is the Weibull scale parameter, Beta is the shape parameter, r^2 is the correlation coefficient, n is the number of samples tested, and s is the number of tests suspended (not completed). The last five samples, each of which was subjected to the three, 20-day aging steps, broke down in the range of 13 to 15 kV, with a 63% probability of breakdown (from the Weibull distribution) of 14.8 kV.

V. DISCUSSION

It is well known that the voltage breakdown of polymeric insulation initiates at imperfections, due to partial discharge caused by localized high voltage stresses. If the insulation contains significant imperfections, then the voltage stresses will precipitate a failure or will cause localized degradation, which in time will lead to premature failure. Neither of these effects was noted while aging the test cable in the laboratory.

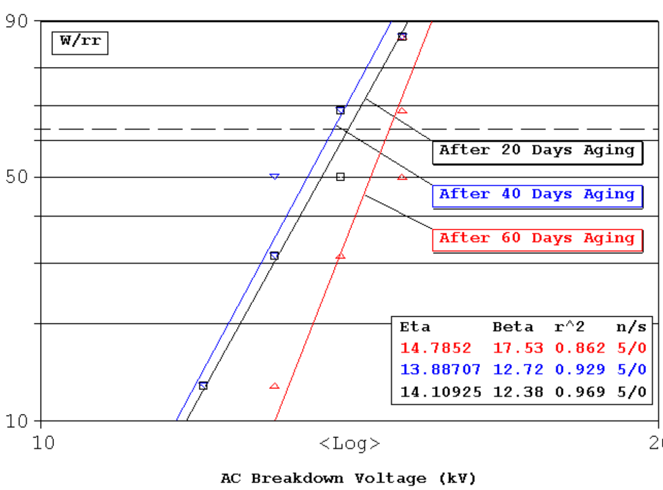

Fig. 5 Weibull plot of aging test results, versus probability in percent.

The aging of these cables for 20 days at three different voltage levels, and the application of progressively higher voltages during the breakdown tests, each for five minutes, can be readily converted to 1750 V aging voltage. Using a formula derived from the inverse power law [10],

$$K = E^n t \tag{2}$$

where K is a constant, E is the voltage stress for cable breakdown in time t, n is a voltage endurance coefficient, and t is the time duration. Since in this case, the test was performed at a number of voltages maintained for specific periods, followed by voltages increasing in steps, equation (2) can be expressed as:

$$E^n t = E_1{}^n t_1 + E_2{}^n t_2 + \mathrm{K} + E_m{}^n t_m \tag{3}$$

where E is the voltage (1750 V) for cable breakdown in time t, and E_1, E_2 …E_m are the aging (test) voltages applied to the cable during test times t_1, t_2… t_m. In the first three terms of this equation, times (t) are equal to 20 days, and subsequently during breakdown tests they are equal to 5 minutes. As noted above, the 5-minute step tests were initiated at 5 kV and increased in 1 kV increments.

For cable insulation aged in a dry environment, n = 10 has been used for medium voltage cables. A lower value of n (for example n = 6), may be used for cables kept continuously in a wet environment. If a very conservative value of n = 6 is assumed for the ROV cables, an equivalent time at 1750 V can be calculated. The calculation indicates that the cable will survive under dry aging conditions for approximately 22.8 years of continuous operation at 1750 V, 60 Hz.

It is recognized that an increase in the aging voltage frequency will result in a faster drop in dielectric strength over time. This fact is attributed to a faster growth of water trees under high frequency conditions. Bahder, et al [11] suggest calculating the frequency acceleration factor, within the measured range, by the expression:

$$F = (f/60)^k \tag{4}$$

where F is the frequency acceleration factor, f is the actual operating frequency, and k is a constant estimated to be 0.6 to

0.7. Using $k = 0.6$, the frequency acceleration factor for 400 Hz vs. 60 Hz is 3, which means that the calculated estimated service life at 1750 V should be divided by 3. In other words, if the cable will be operating at 400 Hz, with the insulation in contact with moisture, the life of the cable would be 7.6 years of continuous operation. However, because this cable operates under dry conditions, the effect of the higher test frequency will be reduced and the cable most likely will last in excess of 15 years of continuous operation.

It must again be emphasized that these time calculations do not take into account the effect of other variables, such as mechanical or thermal stresses, not present during aging in the laboratory.

VI. CONCLUSIONS

Based on the results of the accelerated voltage testing and the obtained voltage breakdown results, the tested cable design should be able to operate within expectations at the proposed phase-to-ground voltage of 1750 V.

Design work is underway at both MBARI and WHOI to exploit the increased power transmission capability made possible by higher allowable cable operating voltages. At MBARI, there are plans to upgrade *Tiburon's* power transmission system above the presently available 15 kW DC. The target is a 50% increase in power, which will enable the vehicle to develop full thrust in two axes simultaneously and significantly increase the maneuvering capability of the vehicle. Since *Tiburon* was designed with a dual, semi-redundant power architecture [12], accommodating the higher power level is not expected to require wholesale modifications to the power system. WHOI is in the process of developing *JASON II*, and has targeted an aggressive power budget as one of the areas for improvement over the original vehicle. Operation of the cable at 1750 V offers the possibility of power levels of 25 kW in a 6000m system, a significant new benchmark in deep ocean scientific ROV capability.

Although the tests described in this paper appear to predict successful cable operation at 1750 V, it will be noted that the aging test did not produce marked evidence of aging effects, in that the cable breakdown voltages were unchanged (within experimental limits) after the most severe aging imposed. This implies that the true operating limits of the cable have not yet been reached. Future test programs subjecting the same cable to more severe electrical stress, for longer periods, should yield results that will be of great interest. Likewise, tests that more closely reproduce actual ROV operating conditions should be considered.

Finally, once the cables' actual performance limits are better known, it may be of interest to explore the possibility of implementing one or more forms of electric field control in the cable core. Based on the authors' experience with utility power cables, it may be possible to further optimize the already impressive performance of these cables, through careful control of insulation electrical stress.

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