

LABORATORY TESTING OF A HVDC SUBMARINE POWER CABLE
FOR THE HAWAII DEEP WATER CABLE PROGRAM

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BY

WILLIAM A BONNET

HAWAIIAN ELECTRIC COMPANY

AND

THOMAS F GARRITY

EBASCO SERVICES INCORPORATED

PRESENTED

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William A. Bonnet
Hawaiian Electric Company
Honolulu, HI

Thomas F. Garrity
Ebasco Services Incorporated
New York, NY

Abstract

The objective of the Hawaii program is to prove the technical feasibility of a commercial submarine power cable system between the islands of Hawaii and Oahu. This represents almost four times the depth and twice the length of present state-of-the-art installations.

Although at-sea testing will be required to verify system management of mechanical loads and insure requisite accuracy of placement, the mechanical, thermal and electrical capabilities of the self-contained oil-filled cable design will be fully characterized in the laboratory with 6,000 feet of test cable.

The laboratory program, the rationale behind its development, and its relationship to other elements of the Hawaii Deep Water Cable Program are described.

1.0 INTRODUCTION

The beginning of the Hawaii Deep Water Cable Program was the 1973-74 energy crisis and the resultant strong public sentiment that the people of Hawaii should be able to do something to protect their economy from a recurrence of that situation. If not entirely, at least partially, the magnitude of effects from political and financial uncertainties in the State's supply of petroleum products had to be reduced. As a state, Hawaii has a very limited ability to influence these international factors, but Hawaii has no such limitation in its ability to become less dependent on foreign petroleum.

Forces were set in motion over ten years ago by the State government to do exactly that. Working closely with major consumers of petroleum, like Hawaiian Electric company, the Department of Planning and Economic Development undertook a systematic look at what the situation was, what it might be in the future, and what could be done about it. The evaluation was published as the Hawaii Integrated Energy Assessment, and its findings were instrumental in the subsequent development of the State Energy Plan.

Of the many observations in the HIEA, three were of particular interest in developing the deep water cable program:

1. At present, over 90% of the State's electrical energy is produced from petroleum products, representing about 30% of the State's annual petroleum import.
2. Over 80% of the State population resides on Oahu, and forecasts indicate that this percentage is not likely to change significantly in the next twenty years or so.
3. Hawaii has abundant sources of renewable energy with the potential to substitute for petroleum in the generation of electric power. The major issues in their development revolve around the technology and the economics of commercial energy production from these sources.

Efforts are already underway by private companies to locate and develop geothermal energy on the Big Island (Hawaii). That resource has the greatest potential of all renewables within the next twenty years to contribute to the State's move toward energy self-sufficiency. The plan is to develop geothermal resources first for the Big Island, and that is on schedule. Current contractual commitments with commercial developers call for 13 MW to be on-line before 1990 and an additional 13 MW in 1991.

In spite of the most optimistic predictions for the future development of the Big Island, the major market for geothermal energy is not there; it's on Oahu, some 150 miles away, separated by ocean depths of over 6,000 feet. If the vast geothermal resources which are indicated in the east rift zone of Kilauea are ever to be developed to their full potential - and if a truly significant substitute for fossil fuel power is going to be realized in the State of Hawaii, the geothermal source and its major market must be brought together.

The best possibility for transporting geothermal energy to Oahu is a high voltage direct current submarine power cable. This technology has been applied successfully elsewhere in the world, and the losses in converting and transporting energy in this manner are minimal. The challenge lies in the fact that no one has ever installed and operated a submarine power cable system to depth of greater than 6,000 feet over distances of 150 miles. The 6,300 foot depth in the Alenuihaha Channel is almost four times deeper than the present state of the art, represented by a cable system between Norway and Denmark. When the financial analysts sharpen their pencils to determine what risk to assign to the debt instruments used to finance the commercial installation, they will seek solid facts to guide their decisions. Investors willing to risk capital in the future development of geothermal wells to produce the energy needed on Oahu must be convinced that there is a feasible technology for export of that energy from the Big Island.

The Hawaii Deep Water Cable Program has been structured to provide those answers; or else geothermal development will remain limited, and Hawaii will remain largely dependent on fossil fuel.

2.0 CURRENT PROGRAM STATUS

The Deep Water Cable Program is an eight-year project involving \$27 million in Federal and State research and development money to prove the feasibility of submarine cable power transmission between Hawaii and Oahu and to provide good, detailed cost estimates for installation and operation. These cost estimates will be used in economic analysis which will establish not whether but when it would be appropriate to begin substituting geothermal power for fossil fuel on Oahu. The technology must be proven, but only the economics can drive the commercial program.

A commercial cable and geothermal development program to supply 500 megawatts of electrical energy would be very capital intensive, on the order of \$1.5 to \$2 billion. However, once that capital investment is made, operating cost will be negligible. This is unlike the present arrangement, where the major expense of electrical energy production is the annual cost of oil. Earlier estimates of the transmission system were \$200 - \$400 million. A study is now underway for the Department of Planning and Economic Development to identify the best organizational structure for ownership and operation of the cable system. When that study has been completed, better assumptions can be made for updating and refining these earlier cable system cost estimates. The major capital component of the overall system is still for geothermal development, and this will be private investors' money under any cable scenario.

The rationale for participation by the federal government in this project rests in the fact that benefits on a national level extend beyond the State of Hawaii. It was mentioned earlier that submarine power cable technology has been applied successfully elsewhere in the world. However, it has been developed by a handful of companies such as Sumitomo in Japan, STK in Norway, Cables de Lyon in France and the Pirelli groups in England and Italy. Their information and expertise remains highly proprietary, not available to the world at large. The fact is that no U.S. company can compete for the commercial installation of a cable system in Hawaii or anywhere else. The methodical approach being applied to the cable design and testing and to installation and repair techniques under the Hawaii Deep Water Cable Program

present an opportunity to create a U.S submarine power cable industry where none exists. When they look forward to possibilities like bringing Canadian or Alaskan hydropower to the western states, or linking the Florida keys and the Bahamas with Florida power, this industry looks extremely interesting.

By contrast, the State government would be completely satisfied if these issues did not have to be researched at all. They would like nothing better than to reach up on the shelf and pull down tried and true technology for application to this project. That would remove one of the uncertainties in the development of geothermal power for Oahu.

An examination of the technology development program for the deep water submarine cable reveals a very complex investigation. This is not merely a desk top study. Sample lengths of this cable have to be built and tested both in the laboratory and at sea. Otherwise, the program's predictive models remain predictive models and its hypotheses remain hypotheses - however good they may be. In the laboratory, the cable must be submitted to all the mechanical and thermal stresses expected for a commercial cable over its minimum thirty year life. There must be assurance by these tests that the cable will not only endure mechanically but electrically. The effect of oscillating bottom currents on a cable under tension suspended between rock outcrops on the bottom must be carefully investigated to understand the failure mechanisms due to fatigue of the critical cable components. At best, these tests will confirm that the cable design has properly considered these kinds of issues and overcome them. At worst, the cable will have to be redesigned and retested. Either way, much more will be known about submarine power cables than anyone knows now.

Even larger than the challenge in cable design is that involved in vessel and cable handling equipment design. There is no vessel anywhere in the world today that could lay the cable selected as optimal for this system. The 6,300 foot depth in the Alenuihaha Channel means that there will be over 60 tons of cable suspended from the vessel. The wind, wave and current conditions which are anticipated in the channel from past records will add a dynamic load estimated at 25 tons, on top of the 60 ton static load. The sea state

conditions encountered regularly in unprotected Hawaiian waters have not been encountered in past submarine power cable projects. The problems that will be faced in the R&D program must replicate faithfully the conditions expected for a commercial application. This represents advancement in the state of the art. The constraints faced by the program in designing the vessel and equipment are formidable. A few of these problems are:

1. Much of the dynamic load imposed by sea conditions cannot be tolerated by the cable; it must be absorbed by the equipment used to deploy the cable. This requires a highly sophisticated means of instrumentation and control, to sense these dynamic forces and automatically regulate the hold-back equipment so that the cable feels only its own weight.
2. If the cable does not have a residual tension on the bottom, it will kink and fail. Accurate measurement of this residual tension over a variety of bottom terrain conditions with slopes as steep as 30 degrees, and feed back of this information to a control system on board the vessel presents a difficult task.
3. The cable can be suspended only for a limited distance between rock outcroppings on the bottom. If that distance is exceeded, the cable will fail in fatigue due to vortex shedding or strumming over time. Location of these outcroppings and accurate positioning of a cable to avoid them are complicated by the fact that it will be some 45 minutes after the cable leaves the vessel and passes through a complex regime of currents before it reaches the bottom.

These few examples begin to give some insight into the purpose behind an eight-year \$27 million dollar program.

Four years into the Hawaii Deep Water Cable Program, a cable has been selected. This selection involved the identification of all the criteria that the cable would have to meet structurally, mechanically, thermally and electrically. It required identification of safety factors for each of these

design criteria, and anticipating how designing for one criterion might impact another. Logically those design computations form the bases for the laboratory testing program. Design calculations have predicted what the cable can do; laboratory testing will find out whether these predictions were right.

Figure 1.0 shows the cross-section summarizing some of the key design features for this cable. The cable is a self-contained oil-filled aluminum conductor cable with contrahelicallly wound flat steel armor. It is roughly 4.7 inches in diameter and weighs about 18 pounds per foot in water. Fabrication of 6,000 feet of test cable is underway and will be completed by the end of June 1986.

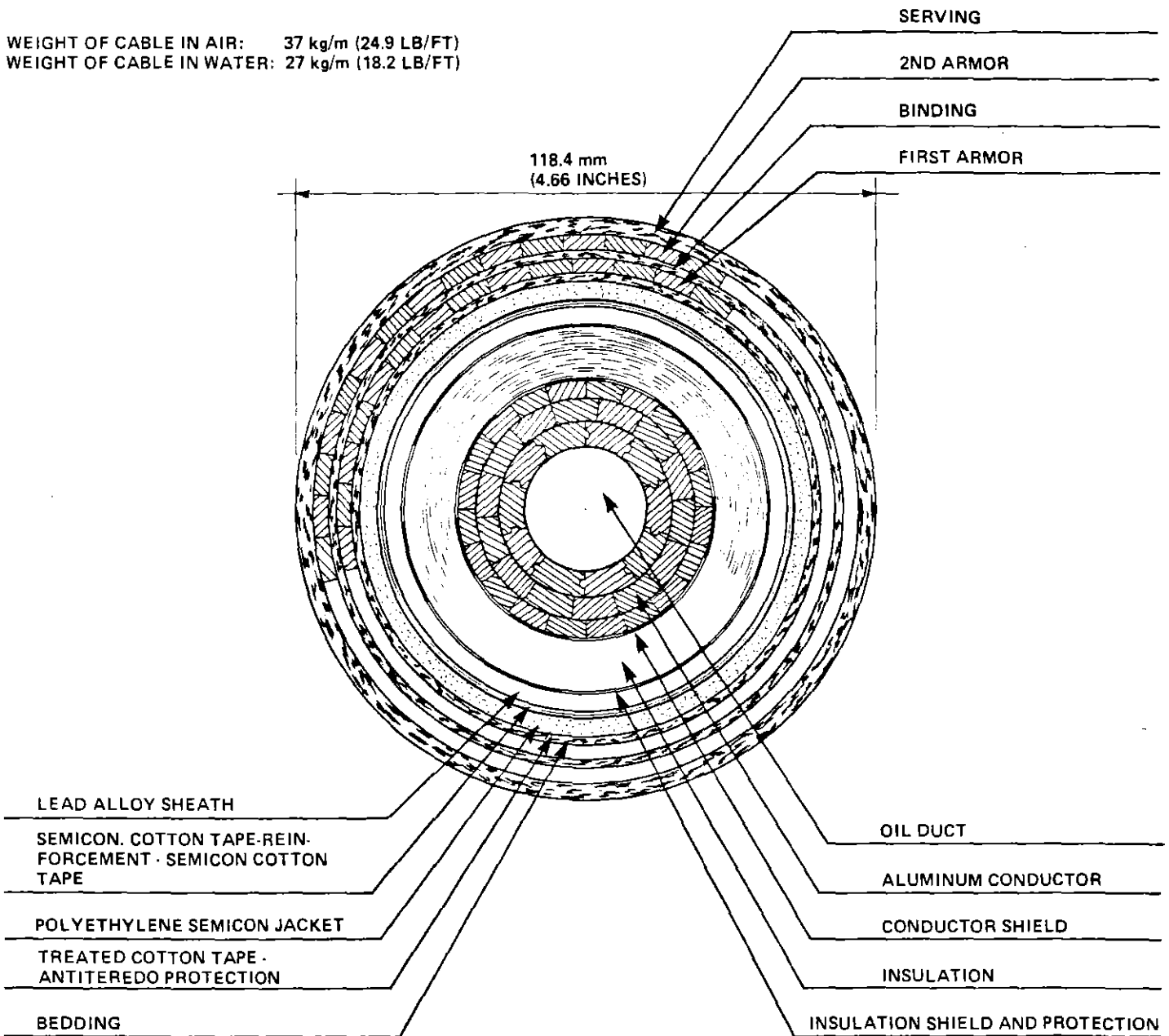
A ten day cruise was completed in early November 1985 to identify actual bottom conditions. The cruise concentrated on what is thought to be the worst part of the cable route: that section of the Alenuihaha Channel called the Kohala Slope, which drops sharply down from a depth of about 3,000 feet to over 6,000. Eventually the entire route will have to be surveyed, but the information obtained from this recent cruise and another scheduled for June of 1986 should provide what is needed to design the vessel and equipment control systems with proper sensitivity.

After the vessel and equipment systems are designed, there begins the expensive and time-consuming tasks of building these pieces of machinery. Most probably, the vessel will be a 250 foot flat deck barge, which will have to be modified for installation of specialized equipment. This will have to be a self-propelled barge, with integral dynamic positioning thrusters. A towed barge could not possibly hold position with the accuracy required.

FIGURE 1.0

SELF CONTAINED OIL FILLED CABLE 1x1600 mm² - 300 kV d.c. HAWAII DEEP WATER CABLE PROGRAM

WEIGHT OF CABLE IN AIR: 37 kg/m (24.9 LB/FT)
WEIGHT OF CABLE IN WATER: 27 kg/m (18.2 LB/FT)



3.0 LABORATORY TESTS OF SUBMARINE CABLE

The laboratory test program has been structured to demonstrate that the selected cable and joints, both factory and repair, are capable of withstanding the expected mechanical stresses and environmental conditions to be encountered during deployment, retrieval and operation while retaining the electrical characteristics necessary for a service life exceeding 30 years. In addition, the testing should be extensive enough to obtain data to optimize the final cable system design.

Qualification tests to establish the baseline performance characteristics of the manufactured test cable will be performed independently of the laboratory exploratory tests, and these qualification tests are tabulated in the Appendix. The detailed Laboratory Test Protocol was developed to demonstrate technical feasibility of the cable system and it incorporates (1) mechanical tests on the cable system to simulate stresses likely to be experienced during installation, recovery and under operation conditions including tidal and bottom currents over at least a 30-year life, and (2) electrical tests to verify a life expectancy of greater than 30-years under the anticipated mechanical stresses. Previous practice, where applicable, was extensively surveyed (1,2,3,4,5,6,7,8,9,10). The test program itself has been further separated into two discrete parts:

- . Individual tests to assess the performance of the cables and joints under single stress worst case conditions; and
- . Sequence tests which accumulate the principal events foreseen in the development and long term operation of the cable and joints.

Charts depicting the two parts of the test protocol are shown in Figure 2.0 and 3.0.

The number of repeat tests specified in the laboratory test program is predicated on the following considerations:

- . Ability to relate test data on models or coupons (in the case of lead sheath fatigue) to the performance of full size cables under operating conditions.

FIGURE 2.0

SUMMARY OF LABORATORY INDIVIDUAL TESTS





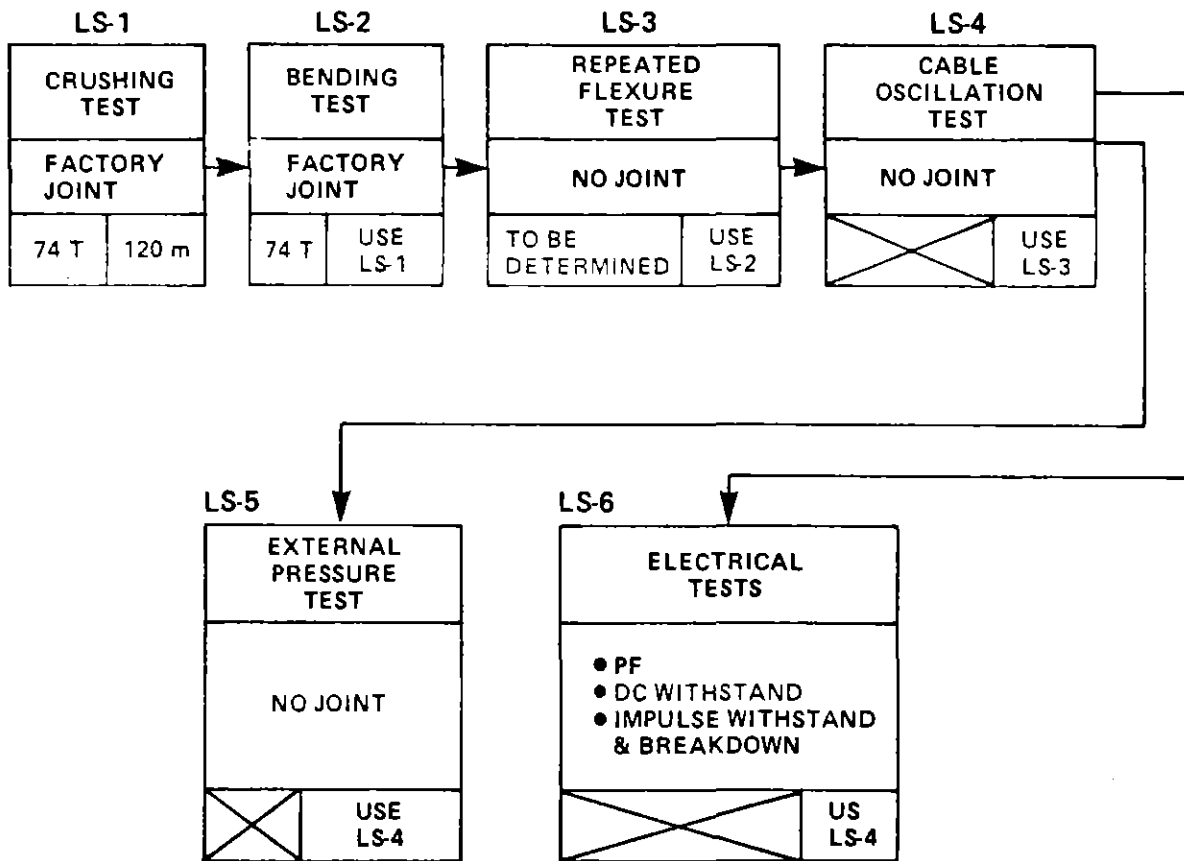
LI-1	LI-2	LI-3	LI-4
BASELINE ELECTRICAL TEST	BENDING & ELECTRICAL TEST	HIGH STRESS TENSILE TEST	REPEATED FLEXURE TEST
<ul style="list-style-type: none"> ● PF ● DC WITHSTAND ● IMPULSE WITHSTAND & BREAKDOWN 	<ul style="list-style-type: none"> ● LOAD CYCLE & POLARITY REVERSAL ● IMPULSE WITHSTAND & BREAKDOWN 	NO ELECTRICAL	NO ELECTRICAL
NO JOINT	REPAIR JOINT	FACTORY JOINT	NO JOINT
 40 m	85 T 120 m	148 T 50 m	TO BE DETERMINED 120 m
LI-5	LI-6	LI-7	
STATIC FLEXURAL RIGIDITY	DYNAMIC FLEXIBILITY RIGIDITY AND DAMPENING COEFFICIENT	CABLE OSCILLATION TEST UNDER TIDAL ACTION	
NO ELECTRICAL	NO ELECTRICAL	NO ELECTRICAL	
NO JOINT	NO JOINT	NO JOINT	
 INCLUDED IN LI-6	 80 m	 80 m	
LI-8	LI-9		
CRUSHING TEST	SLEEVING TEST		
NO ELECTRICAL	NO ELECTRICAL		
NO JOINT	NO JOINT		
85 T 60 m	85 T 80 m		

FIGURE 3.0

SUMMARY OF LABORATORY SEQUENCE TESTS



- . Impracticability of obtaining statistically significant test data on full size cable.
- . Scatter of test data normally experienced in the performance of a specific test.
- . Relative position of the statistical distribution of the test data compared to the level of performance that is required.

In the specific case of self-contained oil filled cable, which is generally true for oil impregnated laminar dielectric cable, the manufacturing process provides extreme uniformity of the insulation which will not be impaired by thermal cycling. Hence, insofar as electrical tests are concerned, a single test is sufficient. In the case of mechanical tests, including those tests that relate to fatigue of the lead sheath, the number of repeat tests specified relate to the criteria mentioned above and are further influenced by the fact that the test conditions have been accelerated compared to the expected stresses during deployment, retrieval and repair operations.

3.1 Summary of Laboratory Individual Tests

The individual laboratory tests are intended to reproduce single stress states on a manufactured test cable to confirm performance of the cable. The mechanical and electrical stresses are calculated to be high enough, or durations of sufficient length, to explore specific failure modes in the cable. The test duties are developed in recognition of appropriate margins of safety between calculated values and test values.

3.1.1 Baseline Electrical Test LI-1

A complete series of electrical tests in accordance with recommended practices outlined by the CIGRE study committee SC-21 (11,12) will be performed on an unstressed sample randomly selected from the manufactured length. With the data obtained from this test, physical degradation of the samples due to testing can be evaluated against the initial quality of the manufactured cable.

Power Factor - The insulation power factor will be measured at voltage stresses of 10 kV/mm and 20 kV/mm in accordance with standard procedures. The difference in measured power factors at 10 and 20 kV/mm, known as the ionization factor, must be 0.0014 or less.

DC High Voltage Test - Since the selected cable system is rated for bipolar operation at \pm 300 kV, the cable sample will be tested at 600 kV (2 pu) for 15 minutes.

Lightning Impulse Test - This test is included to establish an understanding of the cable's basic dielectric strength. The impulse withstand strength of a well made dc cable is expected to be between 100 and 110 kV/mm conductor stress. The lightning impulse will commence at a voltage step of 775 kV (2.58 pu) for both polarities with the conductor temperature maintained at $85^{\circ}\text{C} \pm 5^{\circ}\text{C}$. Following 10 impulses of both polarities, the impulse voltage will be increased in 25 kV steps until breakdown occurs. The breakdown test will be conducted using negative polarity voltage only. For engineering information the cable will be dissected in the region of the breakdown area to determine the breakdown path, and cause of failure. A detailed examination of all components of the insulation structure of the cable will be conducted and reported. Specifically, the tape shield and insulation structure are to be examined for uniformity of gaps, creases, torn tapes and registrations.

3.1.2 Bending and Electrical Test LI-2

The bending test followed by long term electrical testing and impulse tests are intended to demonstrate that the electrical characteristics of the cable and field repair splice will not be impaired by the forces that may occur during at sea deployment and recovery operations.

Bending Test - The bending test is performed to simulate the cable stresses during deployment from a ship as the cable is lowered from the overboarding sheave. Based on the cable design shown in Figure 1.0 and calculated tensions for a 6,300 foot depth of water, a sheave diameter of 39.4 ft (12m) is required for testing the cable. The mechanical set-up for performing the bending test is shown in Figure 4.0.

The cable ends are secured with mechanical heads that are designed to join all metal components of the cable in such a manner as to provide the same distribution of tensile load as experienced during cable deployment. During the bending tests, the cable is subjected to a tension of 85 tons which is calculated using the following formula:

$$T = 1.15 (1.3 Wh + 6.8) \text{ tons}$$

where: W = weight of cable in water
= 0.027 ton/m

h = maximum anticipated depth of deployment
= 1915 m (6300 feet)

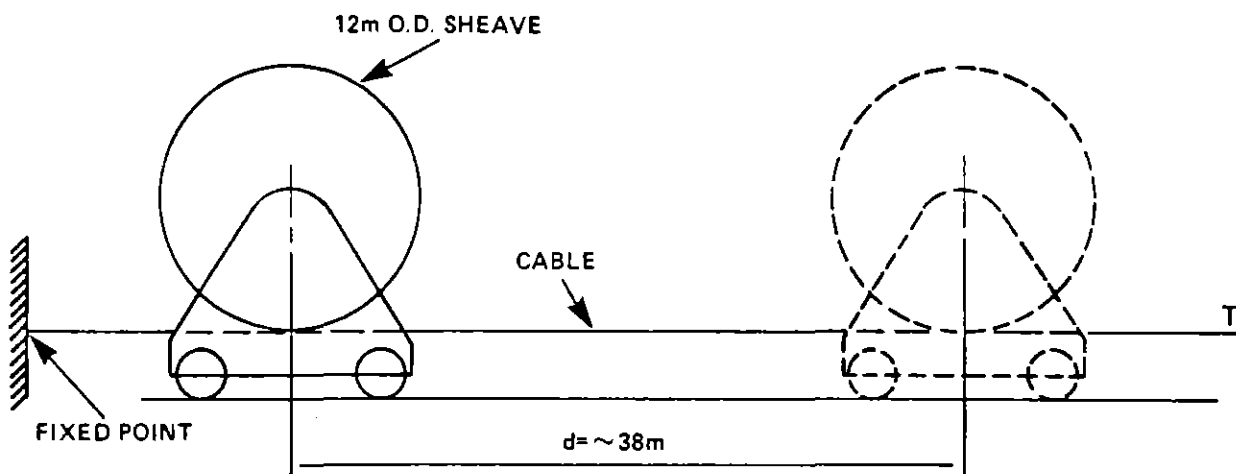
6.8 = residual bottom tension

Load Cycle and Polarity Reversal Test - After the bending test, the cable sample containing a repair joint is subjected to the load cycle and polarity reversal test.

This test, comprising 30 loading cycles, consists of 8 hours heating, at the end of which the conductor temperature is not less than 90°C (maximum rated temperature plus 5°C) and the temperature across the insulation shall be 12°C (maximum design value for this cable application). The 30 loading cycles are divided into 3 tests of 10 cycles each.

The first 10 loading cycles are carried out with a positive dc voltage of 600 kV (2 pu) applied between the conductor and sheath.

FIGURE 4
BENDING TEST



T = APPLIED CABLE TENSION
d = SHEAVE HORIZONTAL DISPLACEMENT

The next 10 loading cycles are carried out with a negative dc voltage of 600 kV (2 pu) applied between the conductor and sheath.

The third 10 loading cycles are carried out with a dc voltage of 450 kV (1.5 pu) applied between the conductor and sheath. Starting with positive voltage the voltage polarity is reversed every 4 hours and one reversal shall coincide with the cessation of loading current in every loading cycle. The recommended time duration for a polarity reversal is maximum of 2 minutes however the time duration may be extended to 10 minutes maximum if the insulation time constant is long.

Lightning Impulse Test - Following the load cycle and polarity reversal test, the cable will be subjected to 10 positive and 10 negative impulse voltages starting with 775 kV (2.58 pu). The conductor is heated to $85^{\circ}\text{C} \pm 5^{\circ}\text{C}$, and after withstanding the rated impulse voltage tests, the impulse voltage is raised in 25 kV steps until breakdown. As with the baseline impulse tests, the cable is dissected in the region of the breakdown area to determine the cause of failure. Should the cable failure not occur within the repair splice, the splice will be dissected for physical examination of all the splice components.

3.1.3 High Stress Tensile Tests LI-3

The purpose of this test is to demonstrate that the cable and factory joint are mechanically strong enough to withstand much higher tensile forces than those anticipated during laying and retrieval operations. Thus an assessment of the mechanical design safety factor of the cable system can be made.

Electrical tests will not be conducted since no assurance can be given about the preservation of the electrical characteristics of the internal insulation after the cable has been subjected to these high tensile stresses. The significance of this test is that if a length of cable is subjected to a tension much higher than the maximum design value, the length will not break but may require replacement.

Tensile Test - The tensile test is usually performed on a long bed tensile testing machine equipped with a suitable measuring device for recording the maximum tension applied to the cable. The cable ends are terminated with suitable heads for application of the tensile load. One head is free rotating.

At the start of the test the tension on the cable is slowly increased to an initial tension value $T_0 = 1.85$ tons which has been calculated by the following formula:

$$T_0 = 50 W \quad \text{tons}$$

where: 50 = length of cable in meters

$$W = \text{weight of 1 meter of cable in air} \\ = 0.037 \text{ tons/m (37 kg/m)}$$

After measurement of the length between two index lines marked on the cable (L_0), the tension will be slowly increased to a value of $T_m = 148$ tons which has been calculated by the following formula:

$$T_m = 2(1.3 Wh + 6.8) \quad \text{tons}$$

where: W = weight of cable in water
= 0.027 ton/m (27 Kg/m)

$$h = \text{maximum anticipated depth of deployment} \\ = 1915 \text{ m (6400 feet)}$$

After holding the tension value for 15 minutes, the length between index lines is measured (L_{max}) and the revolutions of the free head recorded. The tension will then be decreased to the initial value (T_0) and the length between index lines recorded (L_0'). The cycle is repeated three times.

Upon completion of the tensile test, two areas of the cable are dissected one along the unspliced cable and the other at the factory joint. For engineering information, the cable and joint will be

subjected to selective analysis including a) tape shield and insulating tape structure, e.g. uniformity of gaps, creases, torn tapes, registrations, b) damage to lead sheath or reinforcement, and c) condition of conductor, armor and outer covering.

3.1.4 Repeated Flexure Test LI-4

This test is to demonstrate that the lead sheath of the cable can withstand the fatigue stresses that would occur during the construction of an at-sea repair joint under worst sea conditions. Under such a situation, the cable would be repeatedly bent and straightened on the 12 m overboarding sheave due to the pitching of the vessel.

Flexure Test - The test is performed on a sample of cable without a joint and is conducted using a test arrangement as shown in Figure 5.0. The cable is attached to a fixed point at one end and to a tensioning device on the other. The horizontal pulling force to be continuously applied to the cable corresponds to the tension that the cable would experience at the maximum depth at which a repair operation may be conducted on the cable. The maximum repair depth is presently under consideration but 500m appears to be reasonable. The tensile force is calculated by the following formula:

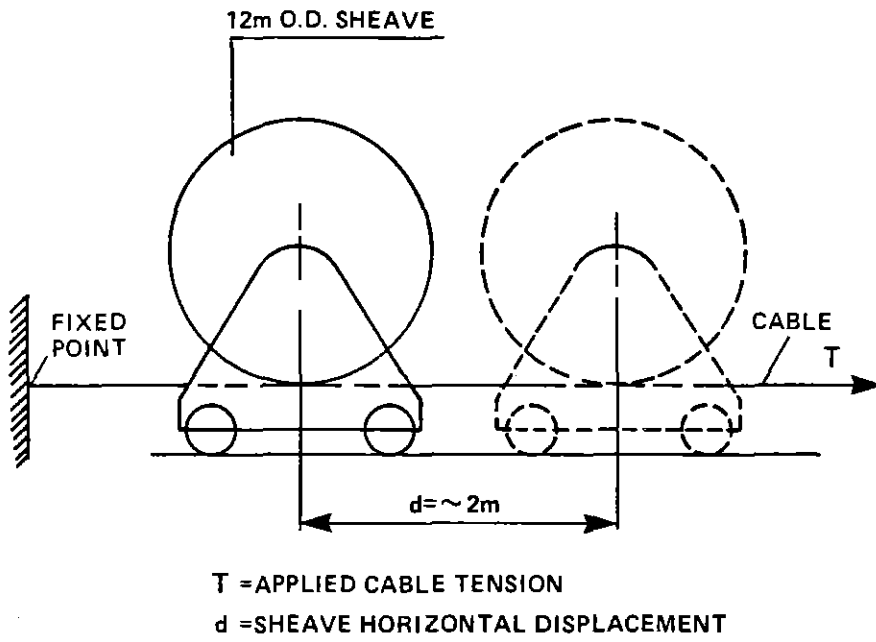
$$T = 1.15 (1.3 Wh' + 6.8) \quad \text{tons}$$

where: W = weight of cable in water
 = 0.027 ton/n (27 Kg/m)

 h' = maximum depth at which cable can be
 repaired (to be determined)

To prevent fatigue of the lead sheath during an actual at-sea jointing operation, a short length of cable would be periodically overboarded thereby moving the flexure point to a new location along the cable. Correspondingly, in this test the 12 m sheave is to be moved back and forth for a distance of approximately 2 m.

FIGURE 5.0
REPEATED FLEXURE TEST



On the assumption that the pitching of the vessel will occur approximately once every 10 seconds (0.1 Hz) and also assuming that a new short length of cable will be overboarded once every six hours, the cable lead sheath at discrete points will be subjected to 2160 flexing cycles during the course of the repair operation. The resultant strain on the lead sheath during each of the 2160 flexing cycles on the 12m sheave is 0.69%.

If the frequency of the test flexures differs from the 0.1 Hz assumed under at-sea conditions, then the number of test cycles N_t to be performed shall be computed by the formula (13):

$$N_t = 1.25 N_s \cdot \sqrt[3]{\frac{f_t}{f_s}}$$

N_t = number of test cycles

N_s = number of at-sea cycles (assumed 2160)

f_t = frequency of test flexures

f_s = frequency of at-sea cycles (assumed 0.1 Hz)

It is presently considered that a suitable value for f_t is in the range of 0.02 to 0.05 Hz.

Upon completion of the repeated flexure test, the cable sample will be physically examined for evidence of mechanical damage to all components particularly the lead sheath. Coupon samples of the lead sheath will be cut from the section of cable subjected to the flexing action and submitted for metallographic examination in comparison with coupon samples cut from unflexed sections of the cable and with recorded results obtained on coupon samples previously subjected to various degrees of flexing/fatigue.

For engineering information, the cable in the flexed area will be subjected to selective analysis including a) tape shield and insulating tape structure, e.g. uniformity of gaps, creases, torn tapes, registrations and b) condition of conductor, armor and outer covering.

3.1.5 Determination of Critical Span Length - LI-5 and LI-6

The following tests are intended to facilitate the determination of the maximum critical span lengths of cable suspensions which are developed when the cable is laid over irregularities on the sea floor and the cable is subjected to tidal and bottom currents.

Since the critical span length of a suspended cable is function of the current velocity, cable dynamic and static flexural rigidities, cable damping coefficient, mechanical tension of the cable at the sea bottom and weight of the cable in water, it is necessary to conduct two preliminary tests in order to perform the calculations. These tests include determination of static flexural rigidity and determination of dynamic flexural rigidity and dampening coefficient.

Measurement of Static Flexural Rigidity (LI-5) - A cable sample will be suspended horizontally with one end fixed and with a constant vertical force applied to the opposite end as shown in Figure 6.0. At both ends, the congruence of all cable components are maintained by means of suitable end caps and clamping devices. The beam length, l , is selected to be in excess of the lay length of the armor. A practical value is 2 m.

The sag of the free end is recorded until a steady state condition is reached. The static flexural rigidity EJ_s is computed by the formula:

$$EJ_s = \frac{l^3}{S} \left(\frac{P}{3} + \frac{WI}{8} \right)$$

where: EJ_s = static flexural rigidity

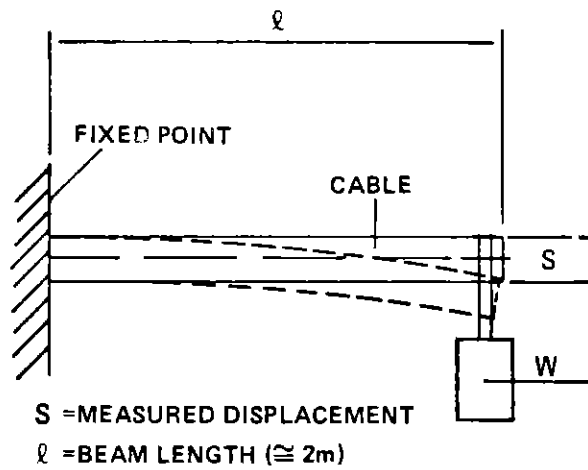
l = length of cable sample

S = beam sag at steady state condition

P = constant vertical force

W = weight of cable per meter

FIGURE 6
STATIC FLEXURAL RIGIDITY
MEASUREMENT



Measurement of Dynamic Flexural Rigidity and Dampening Coefficient

(LI-6) - A cable sample is suspended between two fixed points as shown in Figure 7.0. The cable span between the two sheaves will be 25 to 30 m in length. The cable is subjected to a constant pulling tension so as to produce a sag of 1.3 m in the center of the span. The value of 1.3 m has been determined experimentally to facilitate measurements at the given span length with the cable under a practical value of pulling tension.

A vibrating force is applied to the cable at a quarter of the span length and accelerometers are fixed to the cable to monitor the configuration assumed by the vibrating cable. The frequency of the vibrating force at which the second oscillating mode is imparted to the cable is used to calculate the dynamic flexural rigidity of the cable by means of the following formula:

$$EJ_d = \frac{l^2 (ml^2 f^2 - T)}{4 \pi^2}$$

where: EJ_d = dynamic flexural rigidity

l = length of cable span

m = mass of cable

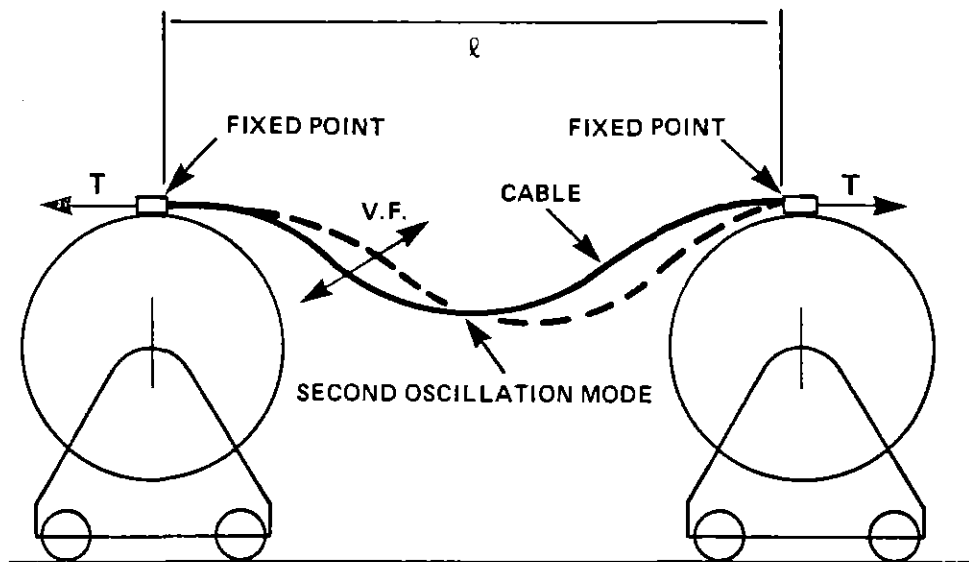
f = frequency of the vibrating force at the second cable oscillating mode

T = constant pulling tension

Using the same test arrangement, the damping coefficient is determined as the mean value obtained by a number of "decay tests" performed by stopping the vibrating force in the range of 0.5 - 1.5 Hz.

The above formula is derived from formula (7) of reference 14 by substituting (a) $2 f$ for the resonance pulsations W_r and (b) $r = 2$ for the mode of oscillation.

FIGURE 7
MEASUREMENT OF FLEXURAL RIGIDITY
TEST AND DAMPING COEFFICIENT



ℓ = SPAN LENGTH
V.F. = VIBRATING FORCE
T = CONSTANT PULLING FORCE

Calculation of Critical Span Lengths - After performing the preliminary tests to measure the static and dynamic flexural rigidity and dampening coefficient, the maximum permissible span length for both tidal oscillations and vortex shedding can be calculated. The bottom current speed from actual current meter measurements and the bottom tension of the cable must be known or assumed.

3.1.6 Cable Oscillation Test Under Simulated Tidal Action LI-7

The purpose of this test is to demonstrate the ability of the cable suspended between two outcrops to withstand tidal movements without experiencing damage to the lead sheath which would limit its life to less than 30 years.

Tidal Oscillation Test - A cable will be suspended between two sheaves with a spacing less than the shortest critical span length (See 3.1.5) and pulled with a 3 ton force. The cable will be made to oscillate with a displacement to the central point of the cable such that the maximum strain at the fixed points will be the same as the strain due to sea current action (see Figure 8.0).

The maximum strain (peak to peak) in the sea bottom conditions is computed as follows:

$$\Delta \epsilon_1 = \frac{D_s}{2} \cdot \frac{F}{T_0} \left(1 - \sqrt{\frac{T_0}{EJ}} \cdot \frac{L}{2} \right)$$

$$F = 1/2 \rho \cdot C_d \cdot D \cdot \Delta v^2$$

where: F = the total force per unit length of the cable during the 12 hours of a tidal cycle

D_s = the lead sheath diameter

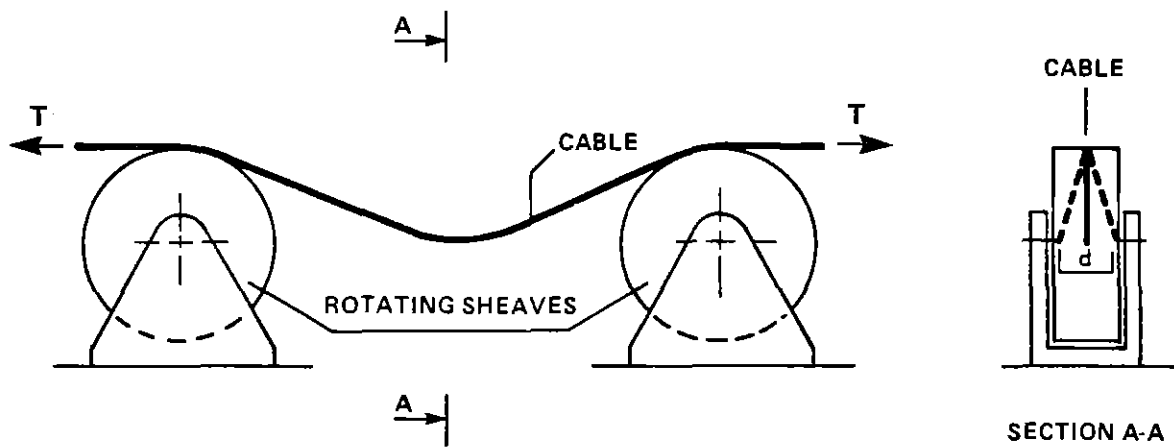
ρ = water density

D = overall cable diameter

$\Delta v^2 = v_t^2 + v_f^2$ = the sum of the squared maximum current speeds in each quarter of cycle of the tide, v_t and v_f are the to - and-fro current speeds

C_d = the drag coefficient

FIGURE 8
CABLE OSCILLATIONS UNDER
TIDAL CURRENTS TEST



T = PULLING FORCE
 d = REQUIRED DISPLACEMENT

The maximum strain $\Delta \epsilon_2$ (peak to peak) under test conditions is computed according to the formula

$$\Delta \epsilon_2 = \frac{24 D_s \cdot d}{L^2}$$

where:

d = displacement imposed to the mid-point of the cable
(peak to peak)

D_s = the lead sheath diameter

L = the span length

By equating the two strains, the peak to peak test displacement is calculated with the following formula:

$$d = \frac{L^2}{24 \cdot D_s} \cdot \Delta \epsilon_1$$

Tides have a frequency of 2 cycles per day. To reduce the testing time, the test frequency will be accelerated to one cycle per second. The test is continued either to failure as evidenced by leakage of oil between the lead sheath and polyethylene jacket or to five times the number of cycles corresponding to a 30 year life (approximately 45 days testing) as computed by the following formula, whichever comes first:

$$N_t = N_s \cdot \sqrt[3]{\frac{f_t}{f_s}}$$

where: N_t = number of test cycles corresponding to 30 year life

N_s = number of cycles at sea corresponding to
30 year life = 22,000

f_t = test frequency = 1 cycle/sec = 86,400
cycles/day

f_s = frequency of at sea = 2 cycles/day

A physical examination of the sample will be conducted for evidence of mechanical damage (leakage of oil) of the lead sheath.

If the test is terminated prior to failure, coupon samples of the lead sheath are to be cut from the section of cable subjected to the flexing action and submitted to metallographic examination in comparison with coupon samples cut from unflexed sections of the cable and with recorded results obtained on coupon samples previously subjected to various degrees of flexing/fatigue.

3.1.7 Crushing Test LI-8

This test is used to determine the maximum withstand crushing force for the cable and to permit calculation of the coefficient of friction of the cable as a function of the crushing force.

Crush Test - A cable sample will be tensioned with a constant pulling force of 85 tons and a linear tensioner simulating device is applied to the cable. The device applies a crushing force to the cable of 3 tons/m while the tensioner is pulled with increasing force. The pulling force that produces a movement of the device with respect to the outer serving or of the outer serving with respect to the armor is recorded. The test is repeated at increased crushing forces of 5 and 7 tons/m at different points along the cable and the pulling forces similarly recorded. The sample will then be dissected for visual examination of the tape shields and insulation structure where the crushing forces have been applied. Specifically, the cable will be subjected to selective analysis including a) tape shield and insulating tape structure, e.g, uniformity of gaps, creases, torn tapes, registrations, b) damage to lead sheath or reinforcement, c) ovalization, d) deformation of polyethylene jacket, and e) condition of armor and outer covering.

3.1.8 Sleeving Test LI-9

The purpose of the sleeving test is to verify the congruence of the cable components (conductor, armor, etc.), during deployment and retrieval operations using a linear tensioner.

Test Procedure - A cable sample is inserted in the linear tensioner simulating device and the maximum permissible crushing force determined in the Crushing Test (3.1.7) will be applied. With this crushing force applied, the conductor alone shall be pulled with an increasing force. The value of the maximum pulling force before displacement of the conductor will be recorded. The test will be repeated by pulling the conductor, lead sheath and polyethylene jacket as a unit. The two values obtained are compared with the computed forces at a pulling tension of 85 tons reduced by the ratio between the lengths of the simulating device and the length of the actual linear tensioner.

3.2 SEQUENCE TESTS

The sequence tests are to demonstrate that the cable and factory joint can withstand the cumulative mechanical stresses arising from a sequence of crushing, bending, repeated flexure and tidal movements simulating cable deployment, retrieval, repair and operation subjected to tidal movements and exhibit satisfactory mechanical and electrical characteristics.

The following tests will be performed in sequence on a cable sample including a factory joint: Crushing Test, Bending Test, Repeated Flexure Test and Cable Tidal Oscillation Test. On completion of these tests, the cable will be divided into two lengths. The shorter length will be subjected to the External Pressure Withstand Test; the remaining length will be subjected to electrical tests including Impulse Withstand Test. The impulse voltage will be increased to breakdown. The cable/joint in the vicinity of the failure and other critical sections of the cable will be dissected and examined for mechanical damage.

3.2.1 Crushing Test LS-1

The device employed for the Crushing Test in 3.1.7 will be applied to a straight length of cable and pulled with a force given by the following formula:

$$P = T \cdot \frac{L_d}{L_t}$$

where $T = 74$ tons (See 3.2.2)

L_d = length of linear tensioner simulating device

L_t = length of actual linear tensioner

P = pulling force to be applied to the test cable

The crushing force in this test will be the maximum withstand crushing force determined in 3.1.7.

3.2.2 Bending Test LS-2

This test employs the same test procedure as for 3.1.2. The tensile force applied to the cable will be 74 tons calculated using the following formula:

$$T = 1.3 Wh + 6.8 = 74 \text{ tons}$$

where W and h are as defined previously.

3.2.3 Repeated Flexure Test LS-3

This test is performed in the same manner as described previously (3.1.4). The jointed section of the cable length will not be subjected to this test.

The tensioning force is computed employing the following formula:

$$T = 1.3 Wh' + 6.8$$

where: W = weight of cable in sea water as defined previously

h' = the maximum water depth feasible for cable retrieval and repair .

3.2.4 Cable Oscillation Test Under Simulated Tidal Action LS-4

This test will be performed as described previously (3.2.5) on the non-jointed section of cable. The test will be terminated after the number of cycles (N_t) corresponding to 30 year life.

3.2.5 External Water Pressure Withstand Test LS-5

This test will demonstrate that the cable can successfully withstand the maximum difference between the external water head pressure and the internal oil head pressure to which the lead sheath is exposed during deployment and in service. This maximum differential pressure across the lead sheath will be experienced in case of loss of the additional oil pressure provided by the oil pumping stations installed at the cable ends.

The cable sample, suitably sealed at the ends by means of caps, will be introduced into a pressure pipe and subjected to a test pressure for 48 hours. The cable will be internally filled with oil maintained at atmospheric pressure. The test pressure will be 20 percent higher than the maximum difference between outer water pressure and internal pressure to which the lead sheath is exposed during deployment or during service.

The test pressure is calculated to be employing the following formula:

$$P = 1.2 (\rho_s - \rho_o) \frac{h}{1000} \quad \text{MPa}$$

where: ρ_s = density of sea water = 10.35 kN/m³

ρ_o = density of cable oil = 9.87 kN/m³

h = maximum anticipated depth of deployment

= 1915 m

3.2.6 Electrical Tests LS-6

The electrical tests described in 3.1 will be performed on the longer length of the cable including the joint after completing the sequence tests described by 3.2.1, 3.2.2, 3.2.3 and 3.2.4.

Failure analysis will be carried out on selected samples using dissection and diagnostic techniques previously described.

4.0 SCHEDULE

The laboratory test program described above is scheduled to begin by October 1986 and could take as much as one year to complete. Capabilities of various electrical and mechanical laboratories to carry out this ambitious test protocol are being evaluated. The overall program schedule indicates sea-trial tests sometime in 1988 and completion of the program by late 1989 or early 1990.

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Appendix

Prior to commencing the laboratory test protocol described in the paper, a series of qualification or type tests are proposed for the manufactured test cable. These tests, as outlined in the relevant Electra articles nos. 68 and 72, are intended to confirm the as manufactured cable in accordance with internationally recognized design tests. The special laboratory tests represent a departure from industry standards, and are exploratory in an effort to probe potential design weaknesses under extreme stress conditions. The qualification tests are summarized in Figure D-1.

The qualification tests can be categorized as follows:

- Q1 - Bending and electrical tests without a joint
- Q2 - Bending and electrical tests with a factory joint
- Q3 - Bending and electrical tests with a repair joint
- Q4 - Tensile elongation test
- Q5 - External pressure test
- Q6 - Internal pressure test

FIGURE A-1

SUMMARY OF QUALIFICATION TESTS

Q-1		Q-2		Q-3	
BENDING & ELECTRICAL TEST		BENDING & ELECTRICAL TEST		BENDING & ELECTRICAL TEST	
<ul style="list-style-type: none"> • LOAD CYCLE & POLARITY REVERSAL • IMPULSE WITHSTAND AND BREAKDOWN 		<ul style="list-style-type: none"> • LOAD CYCLE & POLARITY REVERSAL • IMPULSE WITHSTAND AND BREAKDOWN 		<ul style="list-style-type: none"> • LOAD CYCLE & POLARITY REVERSAL • IMPULSE WITHSTAND AND BREAKDOWN 	
NO JOINT		FACTORY JOINT		REPAIR JOINT	
85 T	INCLUDED IN Q-2	85 T	120 m	85 T	120 m

Q-4		Q-5		Q-6	
TENSILE TEST		EXTERNAL WATER PRESSURE TEST		INTERNAL PRESSURE TEST	
NO ELECTRICAL		NO ELECTRICAL		NO ELECTRICAL	
REPAIR JOINT		NO JOINT		NO JOINT	
85 T	50 m	1.1 MPa	5 m	5 MPa	15 m