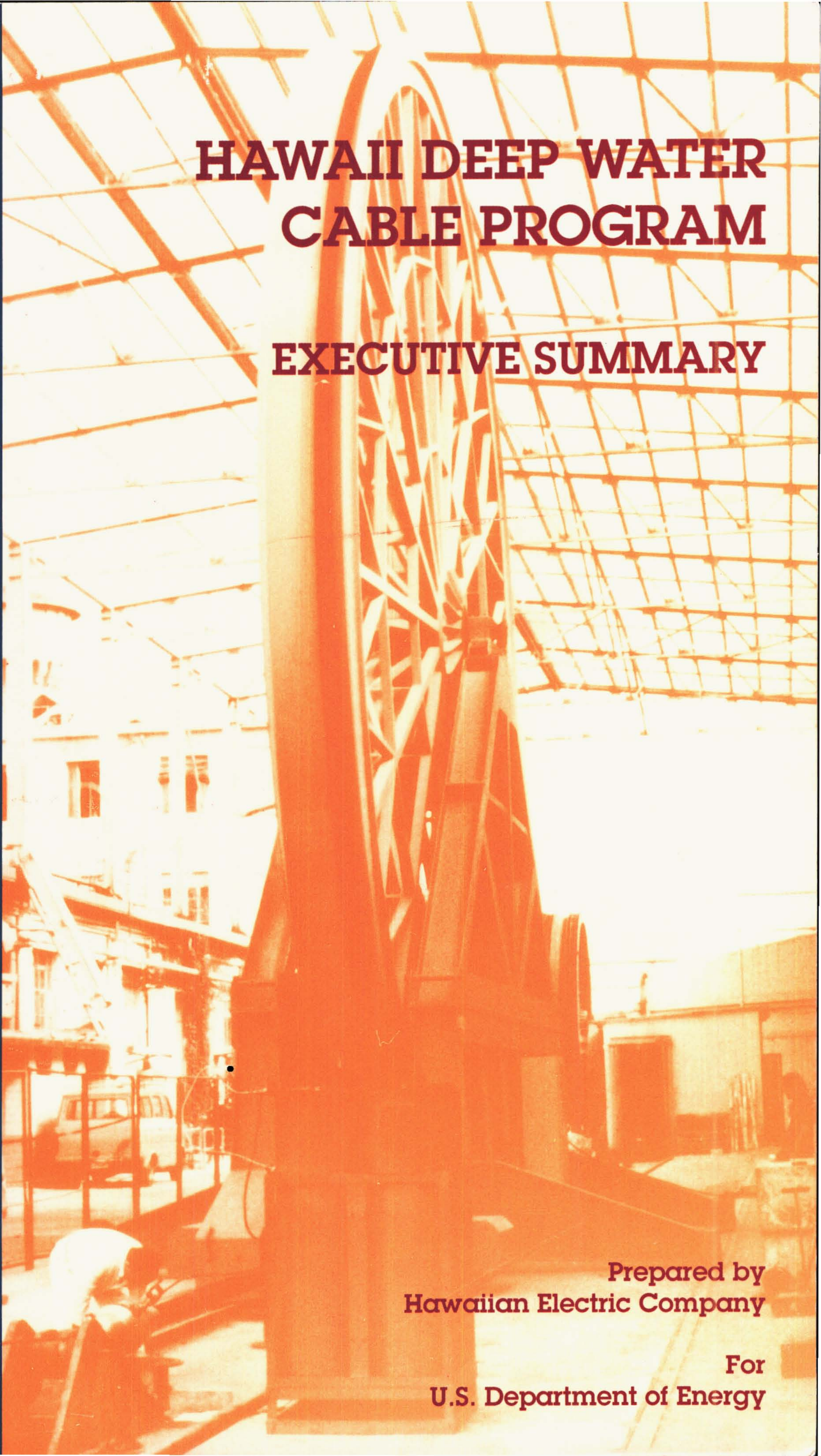
HAWAII DEEP WATER CABLE PROGRAM

EXECUTIVE SUMMARY



Prepared by
Hawaiian Electric Company

For
U.S. Department of Energy

HAWAII DEEP WATER CABLE PROGRAM

Executive Summary
September, 1990

Prepared by
Hawaiian Electric Company

For
U.S. Department of Energy

Produced under contract number DE-AC01-82CE76214

TABLE OF CONTENTS

O V E R V I E W

BACKGROUND

The Arab oil embargo in the 1970's forever altered the consciousness of the American public and their elected representatives with respect to energy supplies and use. Perhaps nowhere in the country was this more acutely felt than in Hawaii, at once both the most isolated of the States and the most dependent upon imported oil for its energy needs. At decade's end, well over 90% of Hawaii's energy was provided by imported oil. Paradoxically, Hawaii has numerous potential alternate energy resources, including solar, wind, biomass, ocean thermal, hydroelectric, and of course, with its active volcano, Kilauea, geothermal.

In the latter half of the decade, geothermal exploration in Hawaii accelerated. A deep research well was drilled into the Kilauea lower east rift zone, yielding maximum bottom-hole temperatures far exceeding those recorded elsewhere in the United States. A 3 MW wellhead generator was installed, and the plant subsequently fed electricity into Hawaii's grid system for the next decade.

As the 1980's dawned, Hawaii was engaged in the most comprehensive integrated State planning effort ever undertaken. The ***Hawaii State Plan*** and its associated ***State Energy Plan*** expressed the strong desire of State government to increase energy self-sufficiency. Completed shortly thereafter was the ***Hawaii Integrated Energy Assessment***, an exhaustive analysis of energy options for Hawaii, which concluded:

> A submarine transmission cable is critical to Hawaii's energy future. Geothermal energy is the only large-scale, indigenous, baseload electricity source that is now commercially mature. The only proven geothermal resources in the state are on the island of Hawaii. The resource is unlikely to be fully developed unless the electricity it produces can be exported to Oahu, which consumes 82% of the state's electricity.

With the mandate of State government and the growing enthusiasm for geothermal development in Hawaii, the feasibility of an interisland undersea electrical cable system remained to be determined. An unsolicited proposal to accomplish this was submitted to the U.S. Department of Energy, and additional funds sought from the Hawaii State Legislature. Initial State funding was provided in 1981, and federal funding began in 1982.

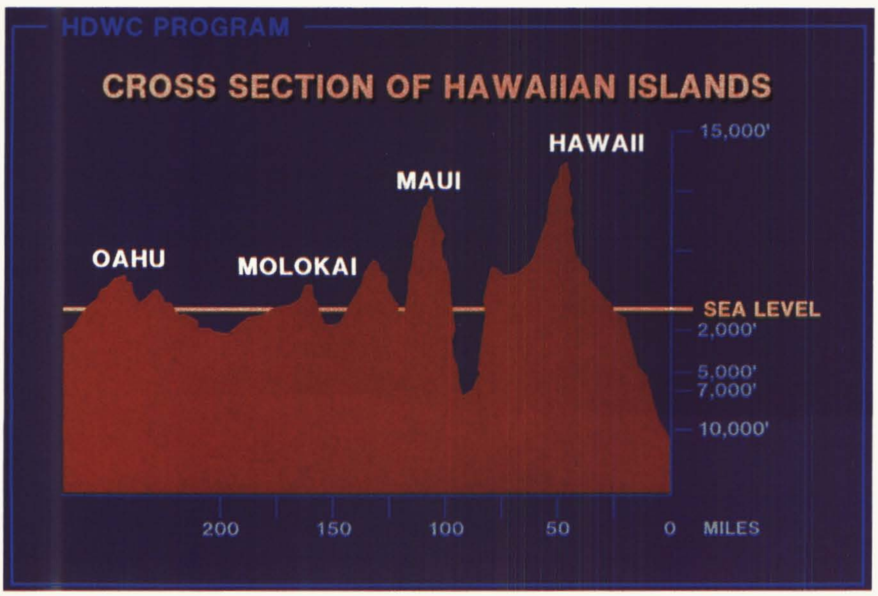


FIGURE 1: Cross Section of the Hawaiian Islands

THE PROBLEM

Any electrical connection between Hawaii and Oahu must include a submarine cable crossing the channel between Hawaii and Maui, the Alenuihaha Channel, where the environmental conditions are extremely severe. In fact, no cable has been laid under such severe environmental conditions. The cable must be laid down the side of one volcanic mountain (Hawaii) to the bottom of the 2,000 meter deep channel and then up the side of another volcanic mountain (Maui) (Figure 1). The path is steep and exceedingly rough, covered with lava flows, boulders and old coral reefs. Ocean currents in the channel are strong and affect both the cable laying procedure and the cable after it has been laid and rests on the rough bottom. The trade winds, increased in velocity by the venturi effect of the two islands, also increase the difficulty of handling a cable laying ship by generating large surface waves and strong surface currents, and by making it difficult for the ship to hold a proper course during cable installation.

If an interconnection between Hawaii and Oahu was to be considered, it was clear that a fundamental question to be answered was: Can the Alenuihaha Channel be crossed with a submarine power cable that will operate for an acceptable length of time?

PROGRAM GOAL

The objective of the Hawaii Deep Water Cable (HDWC) Program was:

> To determine the technical feasibility of deploying and operating, over a service life of thirty years, a submarine power transmission cable between

Kohala on the island of Hawaii and the Makapuu area of Oahu.

It was determined early in the program, based on existing information and program-supported route surveys, that the Alenuihaha Channel was the most severe segment of any route between Hawaii and Oahu. Consequently, if it could be determined that laying a cable across the Alenuihaha Channel was feasible, the feasibility of the complete interconnection would be determined.

FEDERAL/STATE RESPONSIBILITIES

At the highest level there were two groups of tasks in the program. One comprised advances in the state of the engineering art, as no cable had ever been laid in water this deep under the conditions existing in the Alenuihaha Channel. Development of the techniques for successfully achieving the objective of the program would advance the competitive position of the U.S. submarine power-cable industry. These tasks were supported by Federal funds.

The second group of tasks comprised those unique to a commercial application in Hawaii. Among these were measurements of the environmental conditions needed in the cable design and laying operation, the electrical systems studies and the legal, financial and economic studies. These were supported by funds from the State of Hawaii, and are described in more detail later in this report.

THE PROGRAM TEAM

The U.S. Department of Energy provided technical direction and administration of funds furnished by the Federal government. State funds were administered by the Department of Business (formerly, Planning) and Economic Development, with technical direction provided by the Energy Division. The Prime Contractor was Hawaiian Electric Company. Parsons Hawaii provided Program Integration Management. Cable design, development, and testing were done by Pirelli Cable Corporation. At-sea systems evaluation, development and testing were managed by Hawaiian Dredging & Construction Company. Figure 2 is an organization chart of the major contractors.

THE SCOPE OF WORK

The HDWC Program consisted of three phases of work:

- Phase I - Planning and Design;
- Phase II - Cable Design Validation; and
- Phase III - Determination of Cable System Technical Feasibility.

Phase I, funded by the State of Hawaii, established the management systems and overall organization which would serve the remainder of the Program. Completed also were surveys of the state-of-the-art in submarine cables, cable handling systems and cable vessels, as well as a preliminary route survey.

Major technical tasks in Phase II included a parametric study to identify cable designs, cable selection, manufacture of 2,000 meters of the design cable, and laboratory testing of the cable. In preparation for Phase III, final designs were completed for the cable handling equipment, cable vessel controls, and operational equipment. A series of high resolution bathymetric surveys was completed, and an at-sea test plan was prepared.

Phase III consisted of the At-Sea Test itself and all of the subsystem testing, design and procurement directly related to its accomplishment.

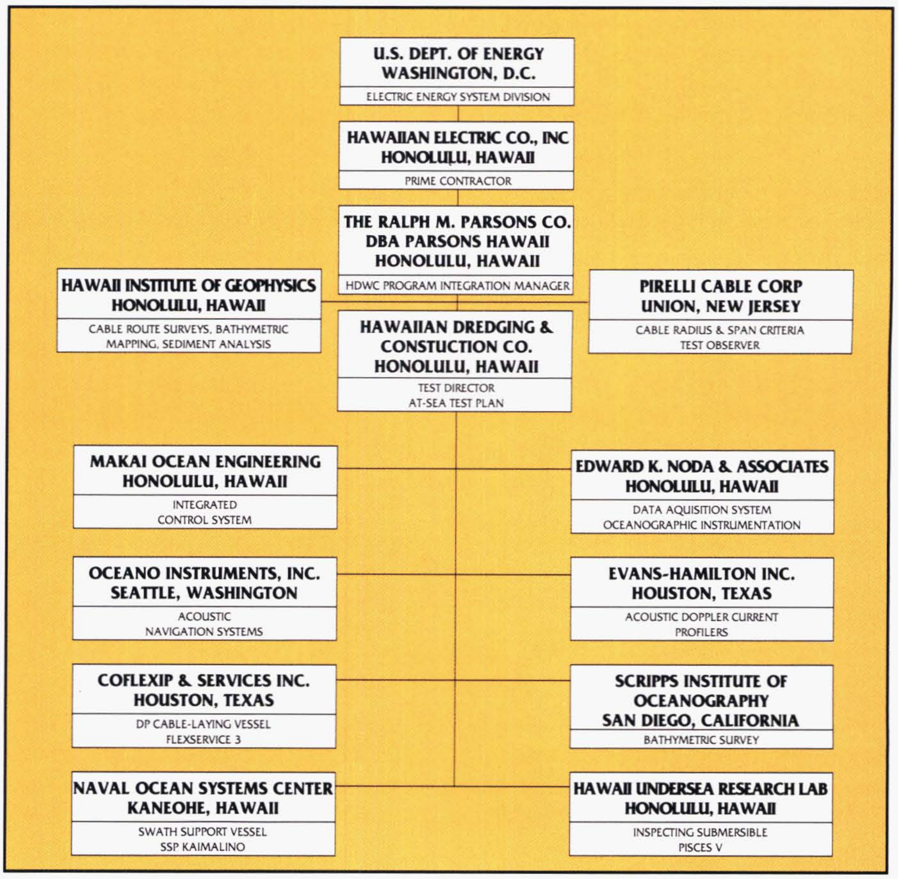


FIGURE 2: Organizational Chart, HWCP, Phase III

THE PROGRAM PLAN

The next step in the development of the program was to answer the question: How do we determine if the submarine cable is feasible? Remembering that the stated program objective required that it be determined whether:

1. A cable could be designed that would operate for at least 30 years (if properly installed); and
2. The cable could be laid successfully, i.e., meet the design requirements of the cable under the existing environmental conditions;

two critical tests were broadly outlined.

The first was to determine if the prototype cable could withstand the forces acting on it as a result of being installed on the ocean bottom, being repaired and operating for 30 years under the existing environmental conditions. This became the Laboratory Test.

The second was to be conducted at sea in the Alenuihaha Channel to determine if the cable could be successfully laid on the most difficult parts of the route: the At-Sea Test.

CABLE DEVELOPMENT

The intention of the HDWC Program was to determine the feasibility of a commercial deep water electrical intertie, not to engage in basic research on untested cable types or components. Consequently, the system feasibility criteria demanded, among other things that, to the greatest extent possible, existing cable design, manufacturing and installation experience be employed, subject to HDWC system verification. Therefore, Pirelli Cable Corporation, in selecting a cable design for potential commercial application, evaluated a broad range of conventional submarine cable designs (several thousand in number). Of these, 251 designs which appeared capable of meeting the cable subsystem feasibility criteria were analyzed by computer in a comprehensive parametric study, and 192 designs did meet the criteria. A third of these were solid cables and the remainder SCOF (self-contained, oil-filled) cables. The important conclusions of the parametric study were that conventional cable technology would suffice for a deep water installation, and that regardless of cable type, aluminum conductor designs could provide the necessary mechanical strength, but copper could not.

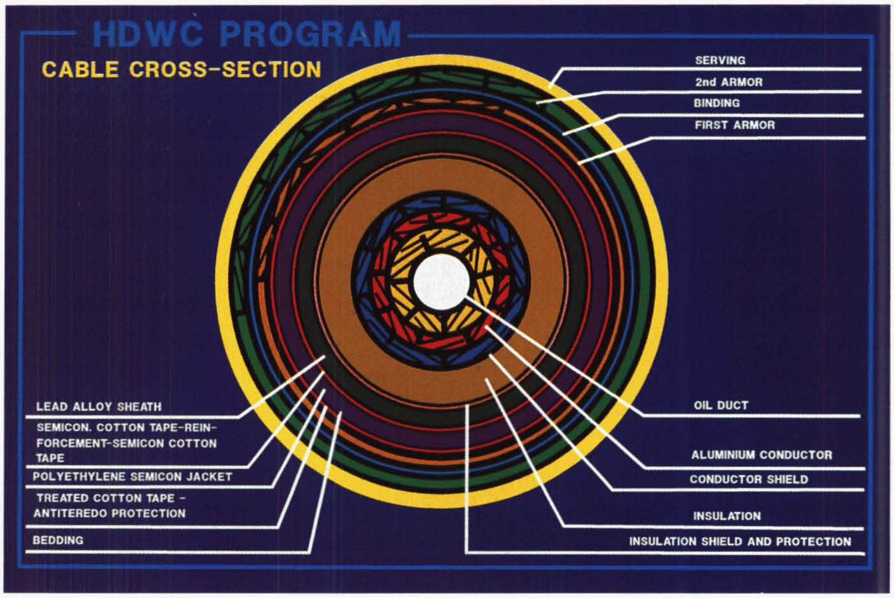


FIGURE 3: Cross Section of the Prototype Cable

To choose the "best" of the 192 designs identified in the parametric study, a quantitative selection methodology was devised to rank the candidates. The top ranked design was a 25mm duct-size SCOF cable having a 1,600 mm^2 aluminum conductor rated at 300 kV, 250 MW that would allow a three cable configuration to satisfy the system requirements.

Following selection of the cable design, a detailed construction specification document was prepared which identified all cable materials, components, fabrication details and materials test requirements and provided quality assurance/quality control guidelines. The specification was sufficiently detailed to permit an experienced cable manufacturer to produce the cable. Figure 3 is a schematic cross-section of the selected cable. Other studies established the minimum radius to which the cable could be bent without damage to internal paper tape insulation layers, and estimated the maximum allowable length of cable which could be suspended between two points on the bottom without unacceptable fatigue of the lead sheath due to oscillation of the span in tidal currents.

LABORATORY TEST

Background. The mechanical loads acting on a cable during its deployment, retrieval and operation depend upon both the cable's design and the environment in which it is deployed and operated. Environmental characteristics such as water depth, ocean currents and winds influence cable deployment. The cable vessel itself is a critical variable. Its length, width, draft and cable overboarding point affect its response to environmental conditions and therefore the loads it imparts to the cable as it reacts to wind, wave and current conditions. The cable handling equipment must hold the cable under tension without crushing it. Once the cable is in place on the bottom, the roughness of the bottom features and the strength of the ocean currents determine stresses due to bending, suspension, oscillation and abrasion.

Objective. It was stated earlier that in order for cable transmission to be considered feasible it was necessary to show that it could withstand the stresses of installation, repair and operation for 30 years and at the end of that time still perform electrically. The purpose of the laboratory tests was to confirm that a sample of the selected prototype cable and factory joint could meet those requirements.

Cable Sample. Two thousand meters of Pirelli's prototype cable were manufactured by Societa Cavi Pirelli in Italy and delivered to their laboratory in Milan.

Test Protocol. The testing of submarine power cables is guided by the recommendations of CIGRE (an international group of cable manufacturers and users) and IEC (International Electrotechnical Commission). Their recommendations suggest methods for conducting the tests and acceptable results. However, a requirement of the HDWC Program was to predict the electrical characteristics of the cable after a simulated 30-year operation in the severe environmental conditions present in Hawaii, conditions that exceeded any encountered in previous cable deployments. Therefore, to supplement the CIGRE tests, a new, more thorough and rigorous test protocol was developed to determine in a one-year testing program if the cable could successfully withstand the mechanical and electrical loads it would experience in its thirty-year design life.

By this time in the project detailed results of measurements of environmental conditions were available, and the test protocol was based on them. The test protocol was composed of two series of tests called the individual tests and the sequence tests. Figure 4 is a schematic summary of the tests in the protocol.

The first individual test was a baseline electrical test that measured the as-built electrical characteristics of the cable, including the voltage required to break down the insulation. Then a series of tests either measured the mechanical parameters of the cable that were needed as data for later tests or subjected the cable to worst-case loads.

The sequence tests subjected one sample of the cable, including a factory joint, to all the loads in the same sequence that it would see in commercial service. At the end of the sequence test the sample would again be subjected to the electrical tests. Its electrical performance would be

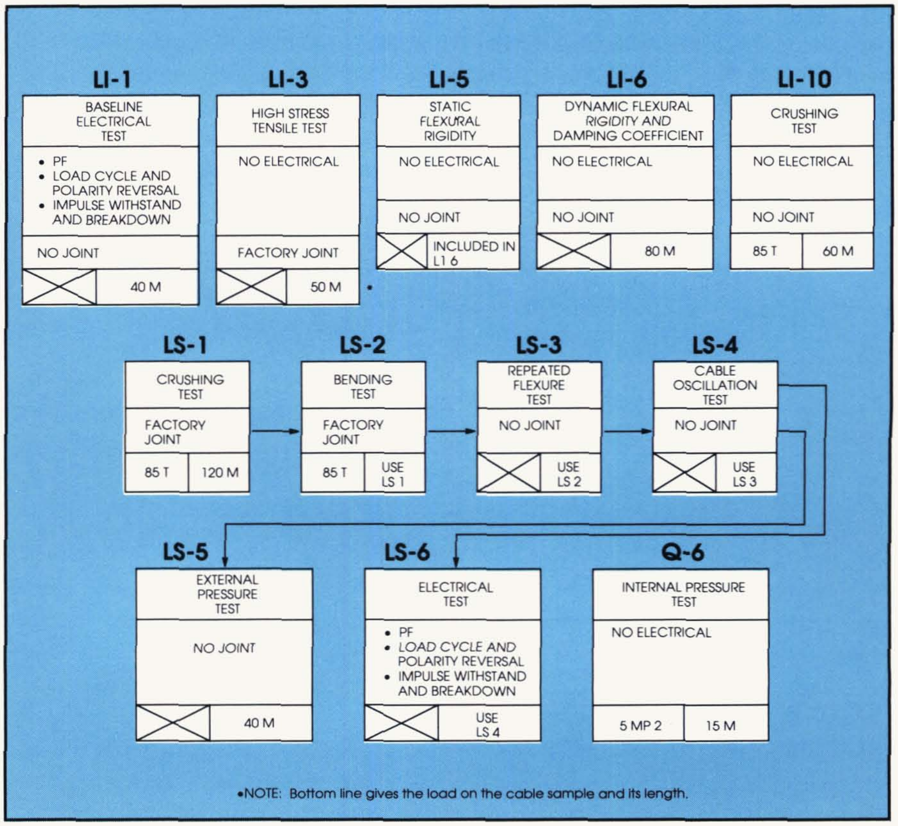


FIGURE 4: Schematic Summary of Laboratory Tests

compared with the performance measured in the baseline electrical test. Any degradation of performance would be attributed to the effects of the simulated installation card and thirty-year service.

Test Apparatus. Because the channel is almost 2,000 meters deep, the cable was heavy due to the armor needed to support its weight. Therefore, the test loads were greater than had been experienced before and there was no laboratory that had the test equipment needed. In December 1987 a contract was awarded to Societa Cavi Pirelli (Pirelli) to design and procure new testing apparatus, modify their test laboratory and conduct the Laboratory Test. Testing was completed in October 1988 in accordance with the test protocol.

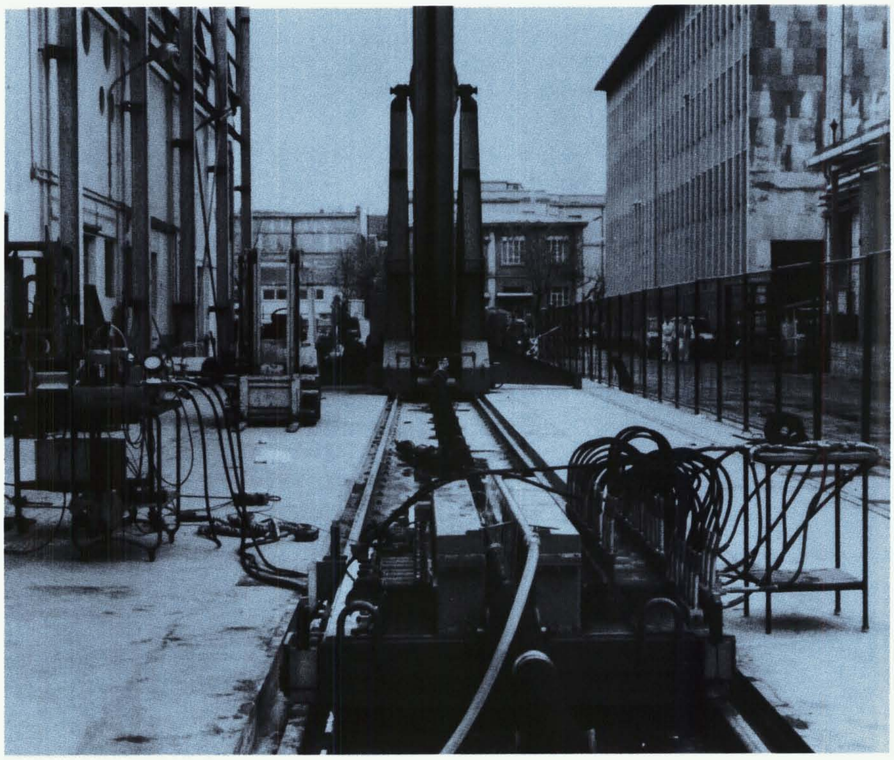


FIGURE 5: Cable in Crushing Test (LI-10) Apparatus

Individual Tests

The individual tests were designed to do three things:

- measure the cable's performance under individual worst-case stress conditions,
- determine selected as-built mechanical characteristics needed in the design of the sequence tests, and
- establish minimum safety factors.

Each test is summarized below.

- ***Baseline Electrical Test (LI-1).*** This test provided baseline electrical data on an as-manufactured length of cable. First, the power factor of the cable was measured; it was in the acceptable range. Then the cable was subjected to load cycles and polarity reversal tests, which the cable withstood. Finally, it was subjected to the lightning impulse test. To be acceptable, the cable was required to withstand positive and negative impulse voltages of 775 kV, which it did. The impulse voltage was then increased in steps of 25 kV until breakdown occurred at 950 kV.

- ***High Stress Tensile Test (LI-3).*** This test determined if the cable and a factory joint could withstand a much higher mechanical load than is expected during laying and retrieval operations. The maximum working load on the cable, including dynamic effects, was calculated to be 74 metric tons. In this test, the cable withstood a load of 148 metric tons, confirming a safety factor on the working load of at least two.

- ***Static Flexural Rigidity Test (LI-5).*** The bending stiffness of the cable is needed to calculate the length of allowable suspension between two outcroppings on the bottom. This value was obtained by suspending the cable under a small tension over two supports and measuring the resulting deflection of the cable.

- ***Dynamic Flexural Rigidity and Damping Coefficient (LI-6).*** The dynamic stiffness and the damping coefficient are needed to assess the likelihood of strumming in the suspended cable due to excitation by bottom currents. The cable, under a small tension, was suspended over two supports and excited at one of its natural frequencies. The dynamic stiffness was then computed. The damping coefficient was determined in two ways: one measured the energy needed to sustain a steady state vibration amplitude; the other measured the rate of decay in vibration amplitude after excitation had stopped.

- ***Crushing Test (LI-10).*** The purposes of this test were to determine the maximum crushing force that the cable can withstand without degrading its mechanical integrity or electrical performance, and to determine the coefficient of friction between the cable and a linear tensioner (Figure 5). The measured coefficient of friction was 0.3.
- ***Internal Pressure Test (Q-6).*** The objective of this test was to determine the cable's ability to withstand the calculated maximum internal oil pressure. A pressure 67% greater than the design maximum acted on the cable for 48 hours, then the cable was disassembled and inspected. No damage was found.

Sequence Tests

The objective of the sequence tests was to observe the cable's response to the cumulative effects of installation and operation for 30 years under extreme fatigue conditions. A length of cable containing a flexible factory joint was subjected to loads in appropriate sequence and then tested electrically to measure its performance after a simulated lifetime of 30 years.

- ***Crushing Test (LS-1).*** The first major load acting on a cable is the crushing load experienced as it goes through the linear tensioner that holds the cable back as it is being laid. Therefore, using a linear tensioner, the joint and the two points that would later become the highly stressed points in the oscillation fatigue test were subjected to a crushing load of 7 tons/meter and a tensile load of 85 metric tons with a working coefficient of friction of 0.15.
- ***Bending Test (LS-2).*** The next stress the cable experiences is a tensile load while bent over the sheave as it passes from the ship to the water. The cable, including the joint, was wound on the 12 meter diameter sheave and subjected to a tension of 85 metric tons. Then, keeping the cable under tension, the sheave was moved back and forth, simulating the overboarding operation.
- ***Repeated Flexure Test (LI-3).*** When the cable is repaired aboard a cable ship, the ship will be stopped and the cable will hang from the overboarding sheave. As the ship pitches, the cable will flex on the sheave, raising the possibility of fatigue damage to

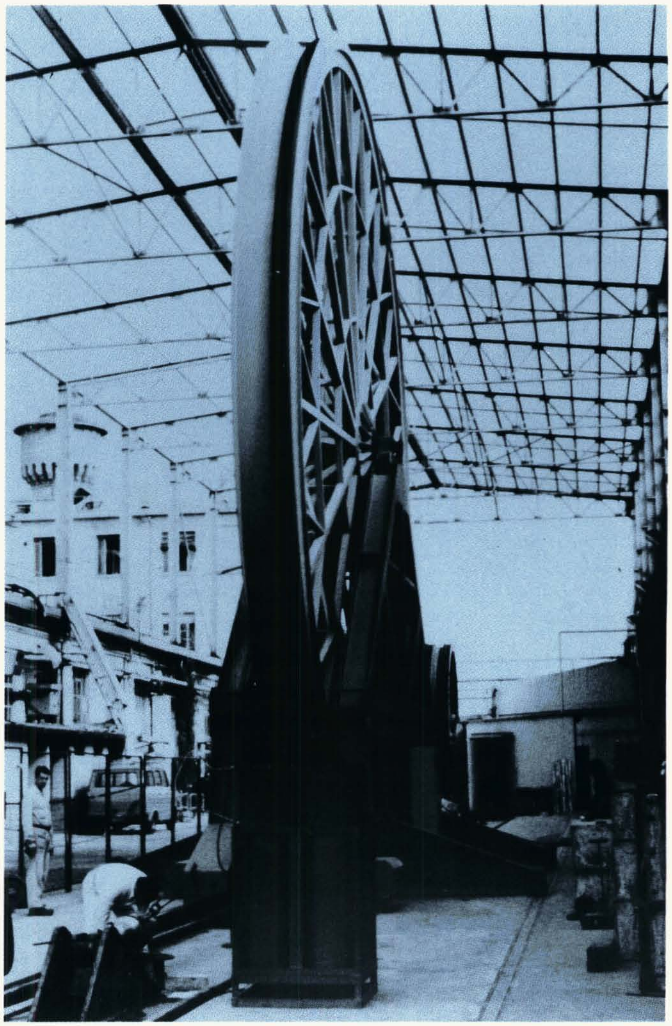


FIGURE 6: 12 Meter Diameter Sheave

the cable. To simulate this condition the cable, under a tension of 28 tons, was flexed on the 12 meter diameter sheave (Figure 6) for six hours at a 10 second period. Subsequently, the cable was disassembled and examined for damage. None was found. A piece of the lead sheath was examined metallographically, and no evidence of incipient fatigue was discovered.

- ***Cable Oscillation Test Under Simulated Tidal Current (LS-4).*** Finally, the cable reaches the sea bottom where it may be suspended between two outcroppings and the daily tidal cycles may cause it to sway back and forth. Over a period of 30 years this swaying motion has the potential to cause fatigue failure of the lead sheath and destroy the cable. To simulate this condition, the cable was suspended between two support points (See Figure 7). At a tension of 3,000 kg, the length of the span was 37 meters, the value computed earlier as the maximum safe span. The cable was displaced at the center of its span by a device that imparted a sinusoidal displacement. The displacement subjected the cable to the same fatigue in 42 days as it would experience on the bottom in 30 years under the actual measured currents.

- ***Final Electrical Test (LS-6).*** After the sequence tests, the cable and joint were subjected to an electrical test identical to the baseline test (LI-1). The cable and joint met all the industry standard requirements and successfully withstood the required lightening impulse of 775 kV. As the impulse voltage was increased, breakdown occurred at 920 kV in the joint.

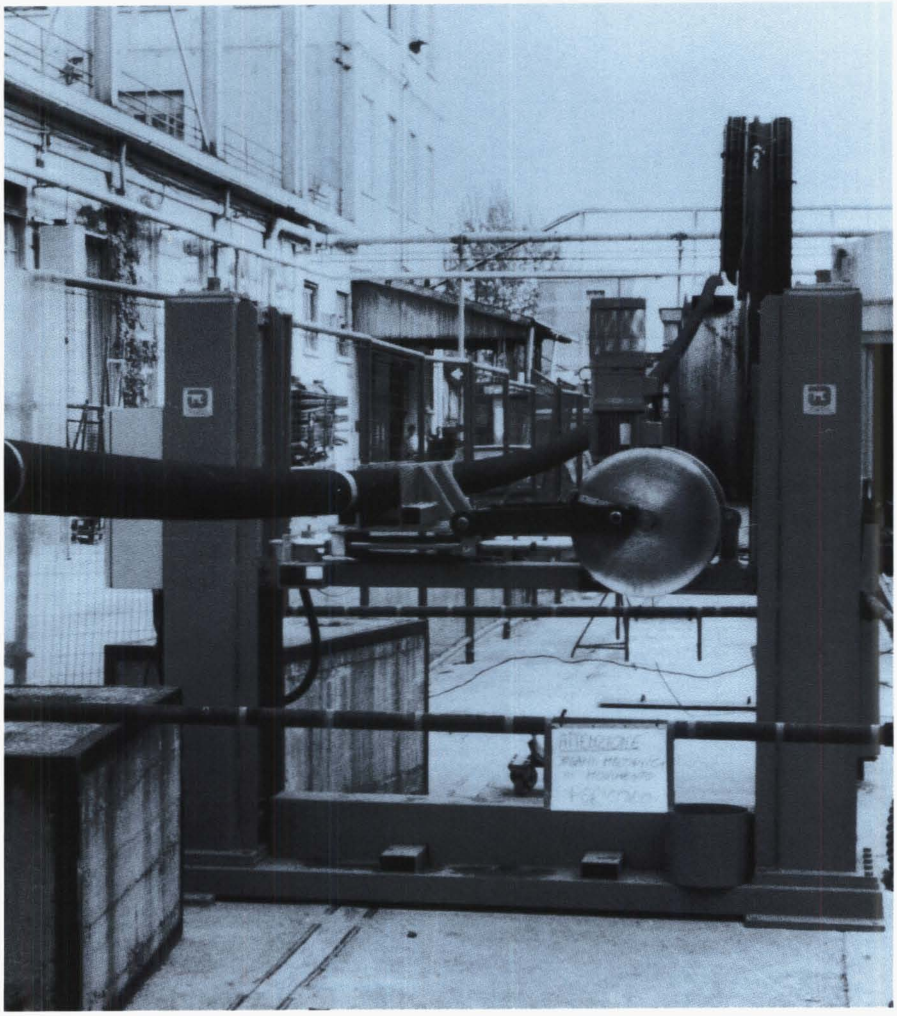


FIGURE 7: Cable in Oscillation Test (LS-4) Apparatus

- ***External Water Pressure Withstand Test (LS-5).*** A cable sample cut from the length which underwent bending was used for this test. It was complete up to the polyethylene sheath. The absence of the external layers increased the severity of the test. The test pressure of 1.1 Mpa, 20% higher than the calculated maximum differential pressure at sea, was applied to the sample for 48 hours. Post-test cable dimensions were compared with the original, and no changes were found.

Conclusions

1. The cable meets industry-recommended electrical and mechanical guidelines for a 300 kV dc submarine cable.

2. Additional mechanical tests that reflect the special conditions of the HDWC Program were conducted, and the cable passed all of these tests.

3. Electrical strength of the cable and joint after a simulated service life of 30 years exceeds the acceptance requirements for a new cable for commercial interisland electrical transmission.

4. There is no evidence that 30 years' simulated service degraded electrical performance of the cable.

AT-SEA TEST

Route Selection

Introduction. To satisfy the objective of the HDWC Program, it was necessary to identify a feasible route for a commercial cable system between the islands of Hawaii and Oahu. Included in considerations of a candidate route were the undersea paths, overland corridors for transmission lines and transition points at the shoreline. A number of preliminary studies identified potential hazards for a cable crossing. A composite "preferred route" is shown in Figure 8. This route would not necessarily be used in a commercial application; however, based on information available, it did appear to be the least intrusive means of transmitting electricity to Oahu.

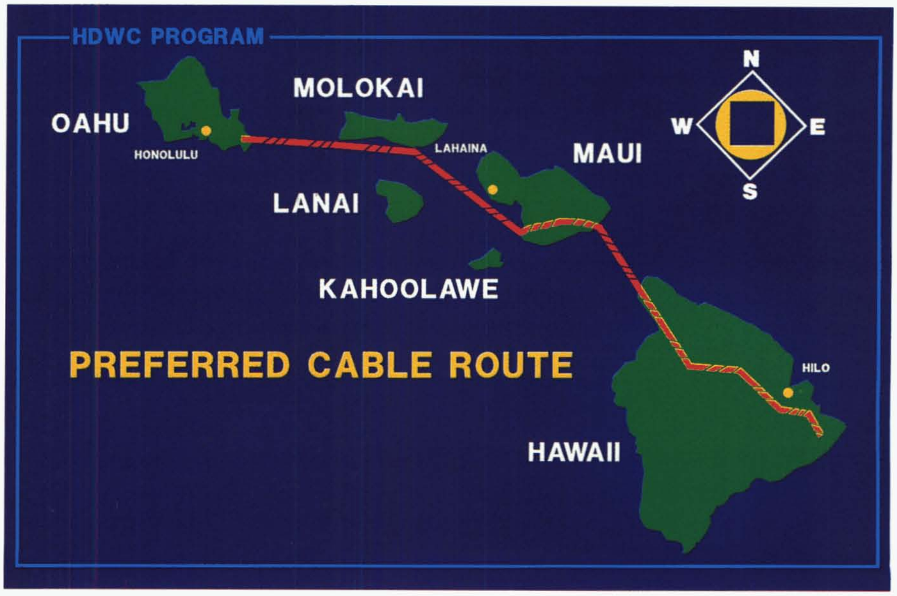


FIGURE 8: Preferred Cable Route

Submarine Cable Route. Cable design work determined, and laboratory testing confirmed, two major constraints to the successful deployment and operation of the cable. First, the cable has a minimum bending radius of 12 meters under maximum tension, and second, the critical span length for a bottom tension of 3,000 kg with the cable subjected to oscillations due to tidal currents is 37 meters. In addition, the maximum height of an outcrop or other bottom irregularity to which the cable could be subjected without damage is four meters. Other constraints included a maximum bottom slope and maximum thermal resistivity of the bottom sediments. All of these factors were investigated, but as development progressed on the integrated control system and at-sea test plan it became apparent that extremely detailed bathymetry would be required. Three bathymetric surveys characterized the seabed along the cable route.

The first survey, undertaken by the Hawaii Institute of Geophysics using SeaMARC, a wide-swath sidescan sonar system, provided an overall assessment of bottom conditions, and identified areas needing more detailed examination. This survey was funded by the Federal government, but the remainder of the submarine route identification work was funded by the State of Hawaii.

A unique "Bottom Roughness Sampler" was designed and built, and a second survey performed using the University of Hawaii's *R/V Moana Wave*. The BRS proved capable of measuring bottom roughness to a resolution of 15 cm. The survey was designed to search for acceptable cable paths by inputting roughness data to a computer program which mathematically "laid" a cable to determine if unacceptable spans and bends would result under various cable tensions. The cruise identified the general level and distribution of roughness along the intended route, and provided confidence that an acceptable route would be found. It remained to the third survey, however, to complete specific definition of a route across the Alenuihaha Channel.

The third survey utilized the Scripps Institution of Oceanography "Deep Tow System." With the results of this survey, a "best" cable path was defined. The "best" cable path was defined as the path with no unacceptable cable spans or bend radii and presenting the least difficulty for cable laying within the survey time and equipment constraints. This latter information was used to define the accuracy required in the cable laying operation as well as to determine the existence of a feasible route.

The remainder of the route, that from Maui to Oahu, was also surveyed in some detail. This was done with another sidescan sonar system, the SSI SeaMARC.

Two areas in the Alenuihaha Channel were found to present the greatest challenges to cable deployment: a narrow, sinuous path up the Haleakala Slope near Maui, and a very steep slope off Kohala, Hawaii. These areas were chosen as the location of the at-sea tests, and were visually inspected using the University of Hawaii, Hawaii Undersea Research Laboratory's submersible, *Pisces V* (Figure 9).

Environmental Data Acquisition

Data Collection. It was necessary to collect extensive environmental data in order to plan and conduct the At-Sea Test. These parameters determined the forces to which the cable vessel, handling equipment and cable itself would be subjected during deployment and operations. Both State and Federal funding supported this work.

A wind measurement station was established at Upolu Point on the Big Island and maintained for a year. Correlations with published data from other stations were used to characterize the annual wind regime in the Alenuihaha Channel. These data were used to establish design criteria for deployment operations.

Similarly, a wave measuring device was stationed in the channel and operated for more than a year. The wave climate was defined and operational design criteria established for cable deployment.

Because of its importance to both laying and operation of the cable, a great deal of effort was expended in gaining an understanding of currents in the channel. Long-term records were generated from meters deployed at various depths and locations in the channel. More nearly synoptic measurements were collected by deploying expendable current probes along a transect across the channel from aircraft and surface vessels. Extensive computer manipulations were performed to sort out the spatial and temporal variability in the four major current components: tidal, wind-driven, eddy and oceanic. The importance of currents to cable deployment required substantial real-time current data collection in the At-Sea Test.

Utilization of Results. The surveys, the cable design, the Laboratory Test and the At-Sea Test plans were interrelated. For example, the cable design influenced route selection because it determined what maximum suspension length would be acceptable. However, the intensity of the bottom currents and the cable design determine the fatigue life of the cable and therefore its service life. The Laboratory Test, therefore, reproduced the cable suspension, and simulated the actual bottom currents acting on it for a 30-year period.

Another more obvious example is that the wind, waves and surface currents determined the dynamic positioning and power requirements of the cable laying vessel. The ability of the ship to hold position, and the currents from the surface to the bottom, affected the design of the cable laying control system.

Systems Integration

Based on the program goal, the objective of the At-Sea Test was to determine if the combined cable laying systems (vessel, control and cable handling equipment) are capable of installing the cable along the selected route with the required accuracy of placement on the bottom and control of residual tension in the cable. As has been pointed out in discussion of the interrelationships of program elements, required accuracy was dictated by cable characteristics, results of the Laboratory Test and environmental conditions.

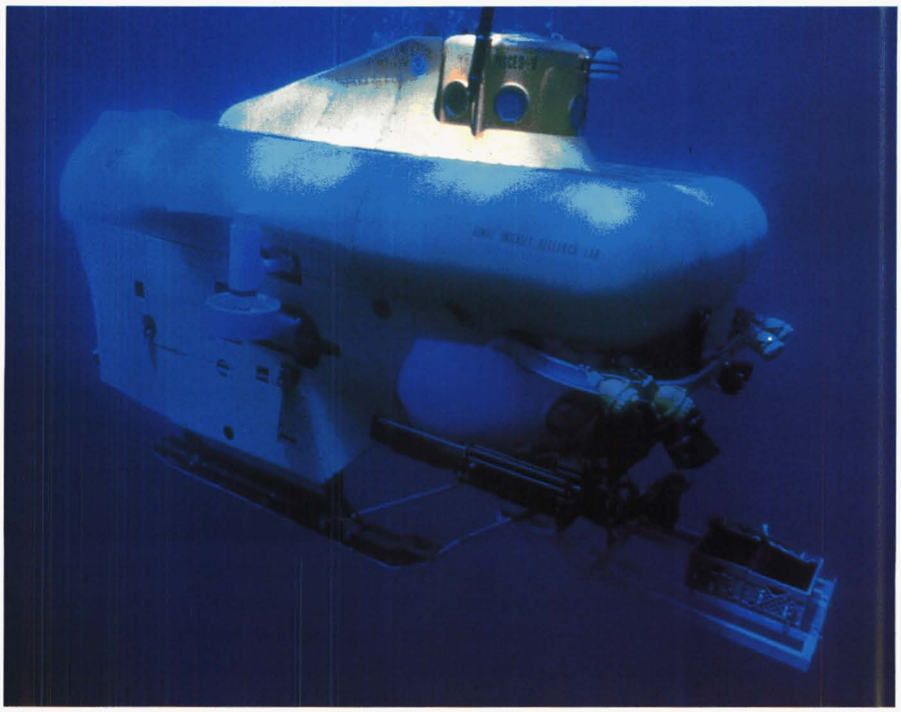


FIGURE 9: The Manned Submersible, ***Pices V***

In planning for the At-Sea Test it was soon discovered that no existing cable laying ship could lay the prototype cable in the deepest part of the Alenuihaha Channel. The load resulting from the heavy cable suspended in 2,000 meters of water was more than any existing cable laying ship could handle.

A considerable effort then went into studying the options that were available to meet the objective of the program, part of which was "to determine the feasibility of deploying the cable."

Three options were studied:

1. Construct a cable laying system using barges, tugs and cable laying equipment designed and constructed for the program (Figure 10).
2. Conduct computer simulations.
3. Use an existing cable laying ship, but use a lighter cable that simulates the prototype cable.

The conclusion of the study was that the first option was unacceptably expensive. The computer simulation, because of the approximations and assumptions that would have to be made, may not be credible. The third option, using a lighter surrogate cable, could meet the objective of the program. It was adopted as the plan of action.

The conceptual approach for the At-Sea Test was to use a surrogate cable with hydrodynamic characteristics (weight/drag) equal to the prototype commercial power cable, a unique cable laying control system and an existing cable vessel with handling equipment. It was shown during the study of the at-sea test options that if the surrogate cable had the correct ratio of weight to drag

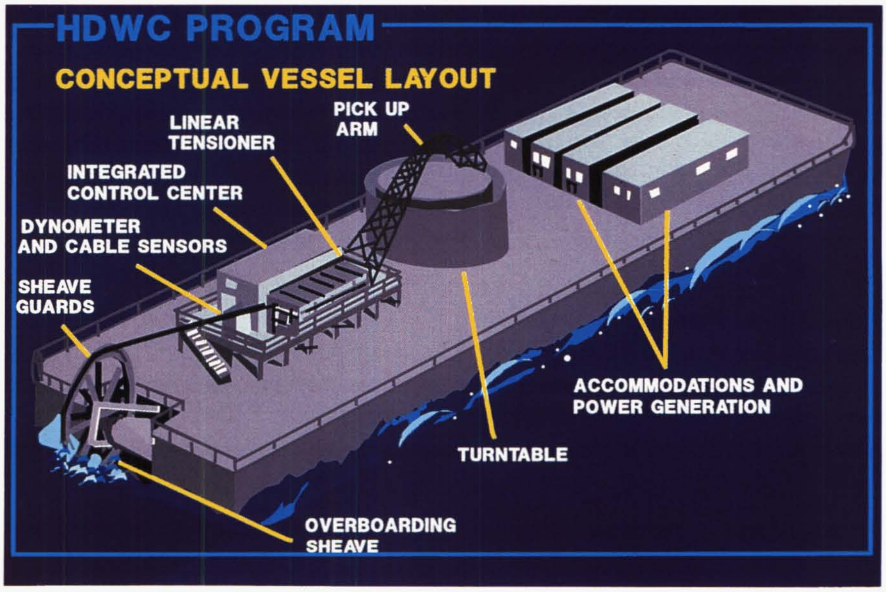


FIGURE 10: Conceptual Cable Vessel and Cable Handling Equipment

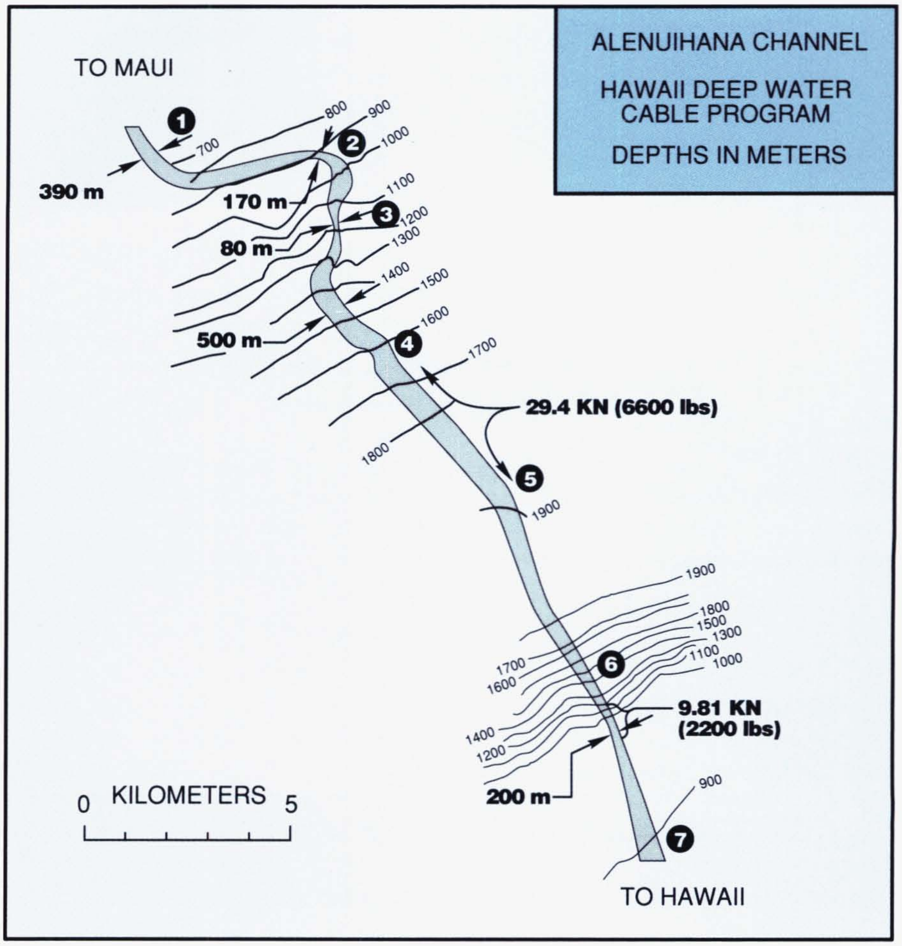


FIGURE 11: At-Sea Test Areas in the Alenuihaha Channel

that the cable laying system would have as difficult a time laying the surrogate cable at it would laying the prototype cable. The two cables would have the same shape in the water and the only difference would be that the tensile loads from the surrogate would be less than those generated by the prototype. The test areas would encompass the most challenging portions of the intended submarine route. The test would determine whether the cable could be placed with the accuracy required by cable design and bathymetric considerations, and the degree to which the amount of residual tension on the cable could be controlled.

Test Site

Figure 11 shows the preferred cable route across the Alenuihaha Channel and the areas selected for the At-Sea Test. This route, the only feasible one identified in the bottom surveys, is difficult because:

- The cable path has multiple bends through areas of seafloor roughness (old shorelines, reefs and lava flows);
- The path is narrow in some areas with a minimum width of 80 meters;
- The path crosses regions of considerable bottom roughness requiring low bottom cable tensions;
- The route is at a significant depth (maximum 1,920 meters), making cable placement and tensioning accuracy difficult; and
- Portions of the route are very steep, with slopes as great as 44 degrees.

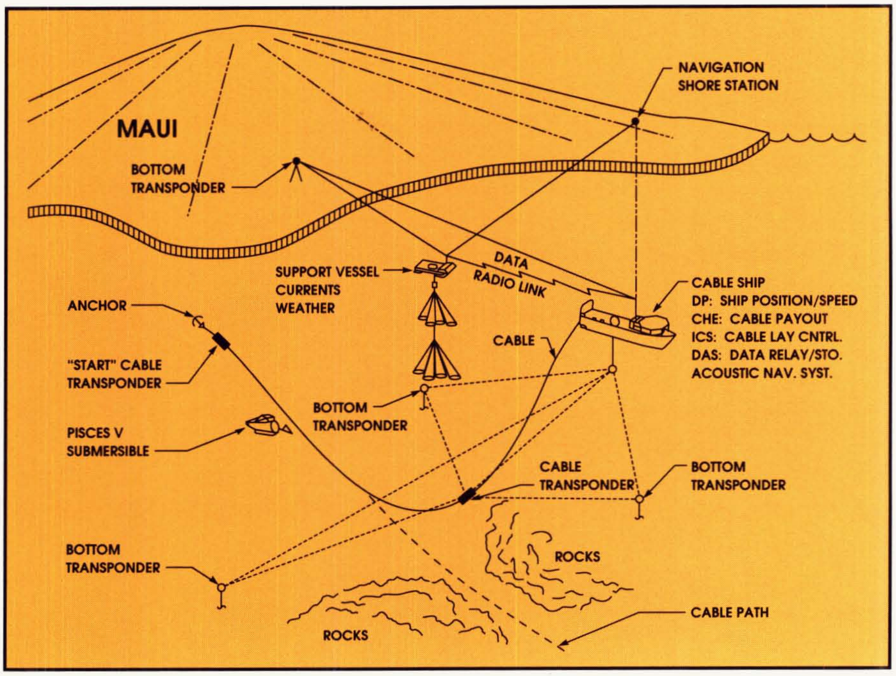


FIGURE 12: Major Systems Involved in the At-Sea Test

The most difficult portions of the route are on the two different sides of the channel. The Maui side of the channel has a very curved and narrow path. The narrowest portion of the entire cable lay, named the "Maui Narrows," is only 80 meters wide at a depth of 1250 meters. This side of the channel has an average slope of 7.5 degrees.

To the south is the Kohala slope which steeply rises (27 degrees average, 44 degrees maximum) from 1920 meters to 950 meters. At the top is a very rough seafloor that was found to be impossible to avoid. Cable tensions were required to be low in this region in order to minimize the potential for an unacceptable span in the cable.

Test Requirements

Test requirements are based upon properly laying the surrogate cable along the predetermined path. A properly-laid cable was defined as one that is accurately positioned and appropriately tensioned on the bottom according to the requirements illustrated in Figure 11. Three cables are planned for this route, so each cable had to be placed to an accuracy of within ± 13 meters (reduced to ± 11.5 meters to account for acoustical navigation errors). Secondary objectives of the At-Sea Test included recording the performance of the cable lay control system and environmental parameters, so that factors limiting cable position and cable tension accuracy could be analyzed in post-test processing, and measuring environmental forces and resulting ship motions to determine their dynamic contribution to total tensile load.

Test Systems

Figure 12 is an illustration of the major systems involved in the At-Sea Test. The components are described below.

- Cable Vessel. The 5,000 ton-dead-weight cable ship,

FIGURE 13: Cable Vessel, ***Flexservice 3***

FIGURE 14: The SWATH Vessel, SSP Kaimalino

Flexservice 3 (Figure 13), laid the cable in the channel. The vessel was equipped with two radio navigation systems ranging to shore stations and providing positional accuracy to within ±1 meter. The vessel also had a dynamic positioning system which computer-controlled its position to within ±3 meters.

- Surrogate Cable. Eight kilometers (26,000 feet) of 45 millimeter (1.75 inch) cable was stored on a large reel and paid out through two 30-ton linear tensioners. The cable was smaller and much less expensive than the prototype power cable. Its weight and drag had been carefully scaled such that the suspended surrogate cable shape would be exactly the same as the prototype power cable, and hence it would be just as difficult to position and tension on the seafloor.

- Acoustic Navigation System. A long-baseline acoustic navigation transponder grid was established on the seafloor and used to track the position of the suspended cable and verify its position on the bottom. The system simultaneously tracked up to seven transponders over a wide area in very deep water.

- Surface Navigation System. To provide a navigational reference system for the positioning of the *Flexservice 3* and the other surface vessels, a radio surface navigation grid was set up on Maui.

- Support Vessel. The small waterplane area twin hull vessel, *(SWATH) SSP Kaimalino* (Figure 14), served as a platform for the current profiling system and its related data acquisition system (DAS). Suspended from it during the tests were two Acoustic Doppler Current Profilers (ADCP) which measured currents through the water column from the surface to the seafloor. Current data were relayed to the *Flexservice 3* via radio modem, and used by the integrated control system (ICS) for calculation of cable position and bottom tension.

- Integrated Control System. This software system accepted all data collected by other systems, including the DAS, to compute past and future cable shapes and touchdown points. As a result of these calculations, instructions for vessel speed, vessel heading and cable payout rate were issued to the ship and cable handling systems.

- The manned submersible, *Pisces V*, deployed from its tender, the *R/V Kila*, dove after

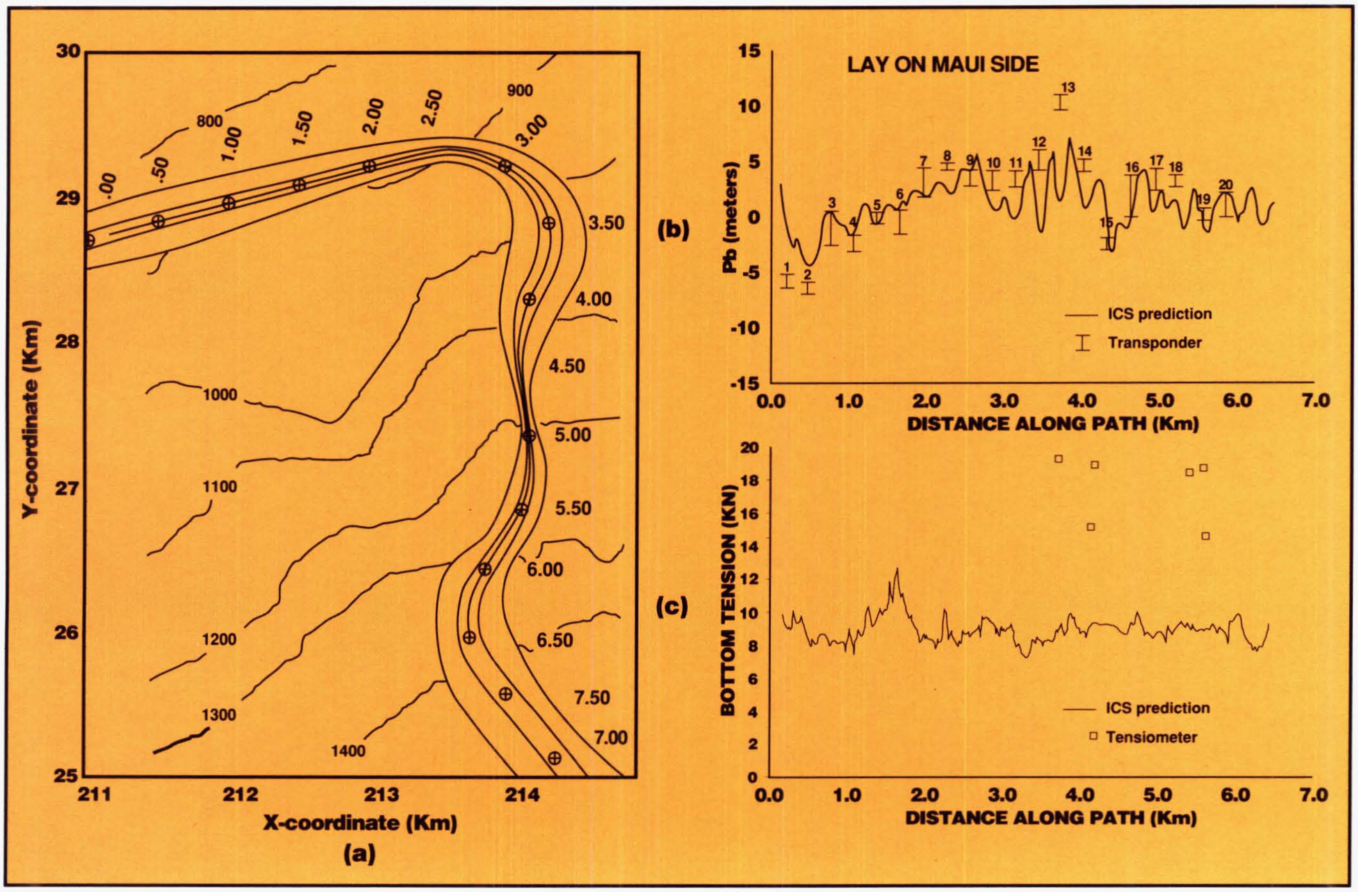


FIGURE 15: Results of the Maui Test Lay

each test lay to observe the cable in place, accurately confirm its position using an attached transponder, and measure residual tensions in the cable.

Preliminary Tests

Major components of the At-Sea Test needed to be evaluated individually prior to their integration in the full-scale test program. These preliminary tests included:

- Proof of Concept cruise, conducted in the Alenuihaha Channel to test the use of the Acoustic Doppler Current Profiler;
- Shakedown Cruise, Phase I, installing and calibrating the Acoustic Navigation System in the Alenuihaha Channel and further testing the current profilers;
- Shakedown Cruise, Phase II, exercising most of the cable laying systems and personnel while laying a 25 millimeter (1 inch) diameter cable in 305 meters (1,000 feet) off Honolulu prior to arrival of the *Flexservice 3*; and
- Dockside Acceptance Tests, conducted in Houston, Texas, aboard the *Flexservice 3*. These tests involved loading the surrogate cable aboard and checking all pertinent ship systems and computer interfaces.

At-Sea Test Operations and Results

The surrogate cable was laid and recovered three times: once on the Maui side of the channel going down slope and twice on the Kohala side going both up-slope and down-slope.

The Maui cable lay is illustrated in Figures 15a,b,c. Figure 15a shows the as-laid cable location on the path. The inner pair of lines on either side of the cable is the cable path width limit for one cable and is one third the total path width (outer pair of lines). Along the cable path are markers, measured in kilometers. Figure 15b illustrates the distance between the actual cable

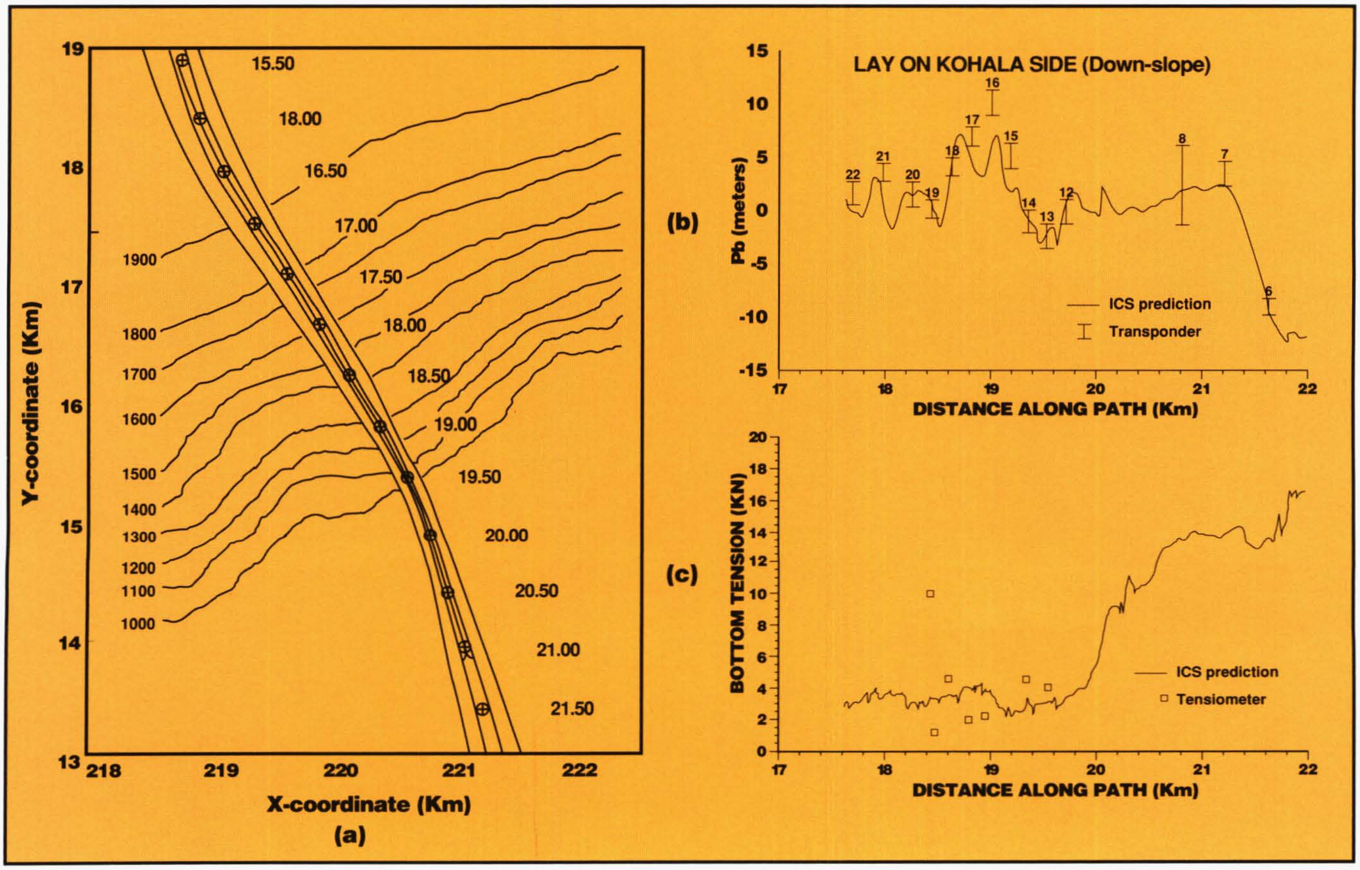


FIGURE 16: Results of the Kohala Down-Slope Test Lay

placement and the ideal cable path, Pb, versus the distance along the path. Figures 15a and 15b show that the cable was placed on the path within the ±11.5 meters allowable tolerance over the entire lay, not just within the Maui narrows.

Figure 15c illustrates the bottom tensions at which the cable was laid. Aside from one area where the cable tension was deliberately increased, the tensions remained well within the test goals.

The second test was on the Kohala side of the channel, laying up-slope to the south. During this lay, the cable was accurately positioned along the path, as on the Maui side, but the cable slid down the steep slope during deployment. Loops and evidence of slack cable were observed by the *Pisces V*. It was concluded that the cable could not be laid up this slope at the low tensions desired, and a second lay was made in the opposite direction.

The third and final lay is illustrated in Figures 16a,b,c. These illustrations show the location of the lay, laying tolerance, and tension tolerance achieved. In Figures 16b and c, the lay proceeded from right to left, with the more critical control requirement starting at the 20 kilometer milestone. The positioning of the cable was well within tolerances. The cable tension requirements were also met. The *Pisces V* conducted dives on those portions of cable on the steep slope and on the rough regions near the top of the Kohala slope. The cable was observed to be straight and uniform with no sign of slackness. Several spans were observed in the rocky region, the two largest at 15 and 20 meters. These lengths were within the maximum acceptable span limit of 22 meters for this tension.

At-Sea Test Conclusions and Recommendations

It was concluded that the surrogate cable was properly laid in the most difficult areas of the Alenuihaha Channel and that a power cable can be properly laid across this channel using the methods developed for and demonstrated in this test. Placement accuracy of the cable far exceeded requirements, and tensioning of the in-place cable met the At-Sea Test criteria.

The laying accuracy required the cable to occupy no more than one third of the total surveyed path, a laying tolerance of $\pm 1/6$ the path width. At no time during any of the cable lays did the ICS error exceed 43% of the allowed tolerance. The mean offset from the desired path of all the transponders placed on the bottom during the three lays was 4.68 meters. In particular, going through the narrowest section of the path, on the Maui side of the channel, the cable touchdown points were kept within 4.0 meters of the desired path.

Several tools essential to the accurate placement of the cable in the Alenuihaha Channel did not exist prior to the At-Sea Test, and their development by the program was necessary. The Acoustic Navigation System was developed as a major extension in depth, range, and number of transponders from an existing commercial system. The current profiling system involved multiple acoustic current profiler instruments that had never before been utilized in a real-time control situation; these were developed into an accurate and reliable sensor system. Also the Integrated Control System developed for this test structured a complex set of cable and environmental models together with a variety of sensor inputs to simultaneously process and filter input data, compute recent cable shapes and touchdown positions, and provide accurate projections of future cable and vessel positions. Each of these systems worked extremely well during the At-Sea Test. Interfacing was excellent, all systems functioned properly, and the few cases of equipment failure did not disrupt the operation because of sound overall system design and contingency planning.

Recommendations for a commercial cable lay include:

- Installation should be from south to north, going down the Kohala slope. Laying up the Maui slope will not present a problem because the slopes are not critical and the allowable bottom tensions are much greater than those on the Kohala slope.
- The cable route should be carefully surveyed for isolated rocks in the path that were not identified in earlier surveys. With the demonstrated cable laying accuracy, these obstacles can be avoided if accurately located beforehand.
- Numerous improvements can be made in the equipment and software to reduce costs and complexity.

CONCLUSIONS

The Hawaii Deep Water Cable Program has succeeded unequivocally in determining the feasibility of deploying a submarine power cable system between the islands of Hawaii and Oahu. Major accomplishments of the program include designing, fabricating and testing an appropriate power cable, developing an integrated system to control all aspects of the cable laying operation, and testing all deployment systems at sea in the most challenging sections of the route.

APPENDIX A

STATE-FUNDED TASKS

INTRODUCTION

Inherent in the objective for federally-funded research is the concept of technology transfer. This criterion was applied to each candidate component of research under the Hawaii Deep Water Cable (HDWC) Program. Issues relating to potential environmental impacts of a commercial application in Hawaii of technology developed under this program were of interest to State government agencies from the inception of the HDWC Program. The same may be said of economic considerations for a commercial application, including the legal and institutional framework within which such a commercial application would take place in Hawaii and the financial mechanisms attendant to commercial development of geothermal resources in concert with a transmission system. And finally, substantial investigation would be required to expand the cable selected under the Federally-funded program into a true transmission system, compatible with the energy resource to be developed and the electric utility system(s) with which it would be integrated.

Each of these considerations is unique to a Hawaii commercial application, and with limited technology transfer potential had limited justification for Federal funding. However, each of the subject areas were as relevant to preliminary planning as was the technical feasibility examined with Federal support. As a result, State-funded research paralleled the Federal program and complemented its findings.

The purpose of this section is to present an overview of research performed under contract to State agencies. Coupled with the bibliography of Federal and State publications from the HDWC Program (Appendix B), this overview should enable those interested in a particular aspect of the program to examine detailed information on that program element with some understanding of its relationship to the program at large. It should be noted that certain State-funded work, namely that involving route identification and environmental data acquisition, was directly supportive of the system feasibility determination, and is discussed in the body of this report.

There are features of the State contracting process for the HDWC Program which must be kept in mind by anyone pursuing information through the documents published under that contract structure.

- The State contracts were in most cases annual contracts, with scopes of work related to Federal efforts, previous findings, and current concerns at that time. Hence, Phases I and IIA-D scopes did not necessarily provide continuity over time; i.e., subject area work undertaken in one State contract may or may not have a counterpart in earlier or later State contracts.
- As a result, the Executive Summary identified for a given phase of State effort is indeed that and no more; in some cases work was superseded in a subsequent phase and in some cases not.
- Particularly in the area of transmission system studies conducted by Power Technologies, Inc. (PTI), an investigator would be well advised to begin with the most recent documents and work backward through time. And again, each PTI summary report must be read only in the context of the scope for that phase; in some cases it is definitive for the program and in other cases the conclusions are altered by subsequent findings.

ENVIRONMENTAL

Investigations were made into a variety of environmental areas relevant to a commercial application of the HDWC Program technology in Hawaii. A significant portion of this effort involved issues related to siting of overland components of a transmission system, including converter stations and facilities for overland to submarine transition. As with many environmental investigations, supporting studies were conducted in areas of particular concern and published as independent documents. These included overland transmission corridor studies, preferred route analyses, environmental review plan, visual impact analysis and others. A scan of document titles in the HDWCP bibliography (Appendix B) will suggest those works whose primary function was to gather and analyze information which would be useful to government agencies and the public in their deliberations regarding a potential commercial transmission system in Hawaii.

This work culminated in August of 1987 with the publication under Phase II-D of an environmental assessment for a hypothetical commercial venture. The environmental assessment format was used since those in both the public and private sectors are familiar with this method of presenting environmental issues. The work did not and could not constitute a formal Environmental Assessment under either Federal or State laws, since this was an information gathering effort only under a research program. The information is intended for use by the State Department of Business and Economic Development in their formulation of a master plan for geothermal/cable commercial development. It is also available to the private sector, prospective developer and citizen alike, as a basis for discussion of a potential commercial venture.

LEGAL, INSTITUTIONAL, FINANCIAL/ ECONOMICS

It was recognized early in the research that the legal and institutional framework surrounding commercial development needed to be explored and that alternative financial approaches needed to be investigated. Although cost estimating was a logical result of the Federally-supported examination of cable designs and vessel/equipment configurations, cost estimates do not yield immediate insight into the economics of commercialization.

In 1984, a study examined legal, institutional and financial considerations for geothermal and cable commercial development. This study was updated in 1986. Results showed no apparently insurmountable legal obstacles to commercialization. Both versions highlighted, as have many other studies of permit requirements in Hawaii, opportunities for more efficient project review. And finally, it put forth a variety of financing schemes but made no final recommendation in this area. Supporting work on cable system installation costs was also done in 1986, analyzing the cost impact of a variety of scenarios for cable fabrication, delivery and installation. This study showed the extreme sensitivity of installed cost to the scheduling of fabrication and delivery of the cable. Additional studies investigated the cost implications of a Molokai overland alternative to submarine transmission over that segment of the preferred route.

All of the work mentioned above, together with a review of the required technical interface among geothermal and cable project components as they could be phased in for compatibility with projected electric utility demand, culminated in the 1988 publication of an economic feasibility study of a phased 500 MW commercial cable/ geothermal venture. Because of the myriad financial, organizational and technical assumptions which must be made, no such study can be considered definitive for a commercial enterprise. Hence, the economic study included sensitivity analyses to show the relative impact of key variables on project economics. Based in part on the findings of this study, as confirmed in review by the Governor's Advisory Committee on Cable/Geothermal Development, both the State Administration and Hawaiian Electric Company determined that commercial development may have economic as well as technical potential, and that the concept should continue to be pursued. As a result, the Department of Business and Economic Development sponsored legislation in the 1989 session to streamline permit processing for geothermal development. They also established contracts to begin work on the master planning for a commercial venture. In 1989, Hawaiian Electric Company issued a request for proposal for a 500 MW private sector geothermal/cable project. Purchase power negotiations continue between Hawaiian Electric company and private consortia as of the preparation of this report in September of 1990.

TRANSMISSION SYSTEM

Power Technologies, Inc. (PTI) was the principal investigator of issues related to the development of an electrical transmission system from the prototype commercial cable. PTI evaluated the feasibility and reliability of various system configurations. They examined the system implications of single and multiple contingency events and the system design requirements to accommodate varying degrees of risk. Given the probable time phasing of development resulting from load growth and unit retirement within the Hawaiian Electric Company system, a three-cable system with sea return appears to be most cost effective.

PTI examined the potential for a tap to provide service to the Maui Electric Company system. Results were not conclusive. While it appears technically feasible to serve the Maui system, the interconnect location would be less than ideal. It would require significant overland transmission, and would in effect provide generation addition near existing generation at Maalaea rather than nearer the West Maui load center where it is needed most. The issue of Maui service from the cable system remains problematic, to be resolved by the parties to a commercial venture and the State regulatory authorities, with public input. However, the work done by PTI provides a meaningful base of information for eventual resolution of the issues.

PTI also investigated the equipment associated with conversion from AC to DC power on the island of Hawaii and re-conversion to AC power and integration with the Hawaiian Electric Company grid on Oahu. PTI identified area requirements for converter station equipment and for the facilities associated with the transition from overland to submarine cable and vice versa. Separate studies examined the grounding requirements for this transmission system, including the equipment and space associated with the recommended shore electrode stations. The converter stations will be major facilities; the transition stations and shore electrode stations will not.

A sub-consultant to PTI studied the potential for load following with geothermal generation. Significant load following would provide substantially increased system flexibility as opposed to strict baseload generation. The sub-consultant identified substantial technical risk associated with significant geothermal load following, and the commercial venture is currently envisioned as a baseloaded system.

OTHER SCIENTIFIC STUDIES

Research efforts with State funds were conducted in a variety of areas where interest arose and Federal funds were either not readily available or not justified under the technology transfer criterion. These included both field and laboratory work.

Although the depth in the Alenuihaha Channel required the only advancement in submarine cable technology, the balance of the route from Maui to Oahu was examined using State funds and state-of-the-art side-scan sonar equipment. This investigation disclosed some areas to be avoided, but showed no conditions which could not be managed with conventional technology in a commercial cable installation.

Submersible vehicles were used to provide photographic and video confirmation of the data gathered by a towed-equipment array. These investigations lent additional confidence to the judgements being made on matters related to seafloor conditions.

The combined effects of abrasion and corrosion on the steel armor of the cable were examined by researchers at the University of Hawaii using facilities at the Natural Energy Laboratory of Hawaii. Using the seawater composition and seabed geologic characteristics to which a commercial cable would be exposed, these studies confirmed that the rate of corrosion, with continued renewal of unoxidized surface metal through abrasion, would not be a significant consideration in the design life of a submarine cable for this particular application.

Finally, friction between layers of cable as a function of tensile load was examined by a researcher at the University of Hawaii. There is no evidence that internal slip, or "sleeving," would be a limiting factor in cable design for a commercial application in Hawaii.

APPENDIX B

HDWCP BIBLIOGRAPHY

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
** SUBJECT AREA: General Management and Administration				
1982	General Management Reports	Parsons Hawaii	Chapman, G.A.	Hawaii Department of Planning and Economic Development
1982	Management Support Reports	Parsons Hawaii	Chapman, G.A.	Hawaii Department of Planning and Economic Development
1984	Program Integration Plan	Parsons Hawaii	Krasnick, G. and G.A. Chapman	U.S. Department of Energy
1984	Technical Standards/ Engineering Procedures Guidelines	Parsons Hawaii	Chapman, G.A. and G. Krasnick	U.S. Department of Energy
** SUBJECT AREA: Cable Subsystem				
1982	Development of Candidate Cable Designs for the Hawaiian Deep Water Cable Program	Simplex Wire and Cable Company		Hawaii Department of Planning and Economic Development
1982	Development of Cable Design for the Hawaiian Deep Water Cable Program (Draft)	Simplex Wire and Cable Company	Traut, R., J. Soden, J. Kurt and R. Costantino	Hawaii Department of Planning and Economic Development
1982	Development of Preliminary Cable Design for the Hawaiian Deep Water Cable Program	Simplex Wire and Cable Company	Traut, R., J. Soden, J. Kurt and R. Costantino	Hawaii Department of Planning and Economic Development
1982	Preliminary Prototype Cable Design Criteria	Simplex Wire and Cable Company	Traut, R., J. Soden, J. Kurt and R. Costantino	Hawaii Department of Planning and Economic Development
1983	Cable Design Reassessment (Draft)	Simplex Wire and Cable Company		U.S. Department of Energy
1985	Cable Transportation from Manufacturing Plant to Hawaii	Hawaiian Dredging & Construction Company	Slayton, M. T.	U.S. Department of Energy

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
1985	Cable Subsystem Feasibility Criteria	Parsons Hawaii		U.S. Department of Energy
1985	Cable Selection Methodology	Parsons Hawaii		U.S. Department of Energy
1985	Test Cable Selection	Parsons Hawaii		U.S. Department of Energy
1985	Cable Construction Specification	Pirelli Cable Corporation		U.S. Department of Energy
1985	Cable Design Parametric Study	Pirelli Cable Corporation Societa Cavi Pirelli	Silver, D., L. and Bonacorsa, G. Bazzi and D. Valenza	U.S. Department of Energy
1986	Cable Overloadability Study	Pirelli Cable Corporation and Societa Cavi Pirelli		U.S. Department of Energy
1986	Cable Catenary Study	Pirelli Cable Corporation and Societa Cavi Pirelli		U.S. Department of Energy
1986	Cable Repair Rationale	Pirelli Cable Corporation and Societa Cavi Pirelli		U.S. Department of Energy
1986	Final Design of Flexible Factory and Field Joints and Terminations	Pirelli Cable Corporation and Societa Cavi Pirelli		U.S. Department of Energy
1986	Cable Repair Rationale	Hawaiian Dredging & Construction Co., Pirelli Cable Corporation and Makai Ocean Engineering		U.S. Department of Energy
1988	Development of Friction Test Specimen for the HDWC System	University of Hawaii, Department of Mechanical Engineering	Knapp, R.M.	Hawaii Department of Business and Economic Development
1989	Cable Laboratory Test Program Report	Pirelli Cable Corporation and Societa Cavi Pirelli		U.S. Department of Energy

** SUBJECT AREA: Cable Handling Equipment Subsystem

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
1984	Sensitivity Analysis of Western Gear's Conceptual Design of a Tensioning System for the HDWC Program	Vega, L.A.		U.S. Department of Energy
1984	Conceptual Design Study: Integrated Control System for the HDWC Cable Laying	Makai Ocean Engineering, Inc.		U.S. Department of Energy

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
1986	Cable Handling Equipment Subsystem Feasibility Criteria	Hawaiian Dredging & Construction Company		U.S. Department of Energy
1986	Cable Handling Equipment Concept Study	Western Gear Machinery Co.	Franchuk, J.M., A. Smith, W. Severe and D. Skiles	U.S. Department of Energy
1986	Conceptual Design Study: Integrated Control System for the HDWC Cable Laying (Revised)	Makai Ocean Engineering, Inc.		U.S. Department of Energy
1987	Cable Laying Control and Data Acquisition Systems, Preliminary Design Report	Makai Ocean Engineering, Inc. and Edward K. Noda & Associates		U.S. Department of Energy
1988	Cable Laying Control and Data Acquisition Systems: Final Design Report	Makai Ocean Engineering, Inc. and Edward K. Noda & Associates		U.S. Department of Energy
** SUBJECT AREA: Cable Vessel Subsystem				
1982	Preliminary Cable Ship Inventory and Capabilities	Morris Guralnick Associates, Inc.		Hawaii Department of Planning and Economic Development
1982	Cable Deployment Program Cost Estimates and Cable Vessel Concept Design for Hawaii Deep Water Cable (HDWC) Program	Morris Guralnick Associates, Inc.		Hawaii Department of Planning and Economic Development
1982	Preliminary Cable Ship Inventory and Concept Design	Morris Guralnick Associates, Inc.	Richardson, R.K.	Hawaii Department of Planning and Economic Development
1983	Reassessment of Cable Vessel Availability	Hawaiian Dredging & Construction Company	Lopez, L. and F. McHale	U.S. Department of Energy
1986	Cable Vessel Subsystem Feasibility Criteria	Hawaiian Dredging & Construction Company	Slayton, M.T., and F. McHale	U.S. Department of Energy
** SUBJECT AREA: Electrical Grid System				
1983	Preliminary Electrical Grid System Integration Study	Hawaiian Electric Company	Imai, R.M., G.N. Okura and T.C. Simmons	Hawaii Department of Planning and Economic Development

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
1984	System Studies (4 Vols.)	Power Technologies, Inc.	Mountford, J.D.	Hawaii Department of Planning and Economic Development
1986	Phase II-B System Studies (3 Vols.)	Power Technologies, Inc.	Mountford, J.D., A.J. Wood and M.A. Sager	Hawaii Department of Planning and Economic Development
1986	Hawaii - Oahu HVDC Interconnection Simulator Study	Power Technologies, Inc.	Johnson, B. K.	Hawaii Department of Planning and Economic Development
1987	HDWC PHASE II-C System Studies	Power Technologies, Inc.	Mountford, J.D.	Hawaii Department of Planning and Economic Development
** SUBJECT AREA: System Integration and Testing				
1983	System Analysis and Parametric Studies for the Hawaii Deep Water Cable Program: Task 1.1, Literature Survey	EG&G Washington Analytical Services Center, Inc.	Hoech, J.	
1984	System Analysis & Parametric Studies	EG&G Ocean Systems and Makai Ocean Engineering, Inc.	Vega, L., G. Nihous, J. Hoech, J. Van Ryzin and A. Resnick	U.S. Department of Energy
1985	Basic Design Criteria Data Book	Parsons Hawaii		
1985	System Feasibility Criteria	Parsons Hawaii		U.S. Department of Energy
1985	Evaluation of Options for At-Sea Testing (Revised Draft)	Pirelli Cable Corporation and Societa Cavi Pirelli		U.S. Department of Energy
1985	System Test Plan: Test Objectives, Requirements and Rationale (Final Working Draft)	Parsons Hawaii		U.S. Department of Energy
1985	Summary of HDWC Program Minimum At-Sea Test Requirements	Hawaiian Dredging & Construction Company	McHale, F. and L. Lopez	U.S. Department of Energy
1985	Preliminary Report on Evaluation of Options for HDWC At-Sea Tests	Hawaiian Dredging and Construction Company, Inc.	McHale, F., L. Lopez and J. Van Ryzin	U.S. Department of Energy

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
1985	Objectives and Tests for Laboratory Testing of Cable and Joints for the HDWC Program	Pirelli Cable Corporation		U.S. Department of Energy
1986	Selection and Design of Laboratory Testing Equipment	Pirelli Cable Corporation and Societa Cavi Pirelli		U.S. Department of Energy
1986	Laboratory Test Protocol	Pirelli Cable Corporation and Societa Cavi Pirelli		U.S. Department of Energy
1986	Laboratory Testing of a HVDC Submarine Power Cable for the Hawaii Deep Water Cable Program	Hawaiian Electric Company and Ebasco Services Incorporated	Bonnet, W.A. and T. F. Garrity	
1987	Conceptual Design of Reduced Scale At-Sea Test (Draft, 2 Vols.)	Hawaiian Dredging & Construction Co. and Makai Ocean Engineering	Hee, R., F. McHale, M. Slayton, L. Lopez, J. Van Ryzin, J. Andres and G. Sheu	U.S. Department of Energy
1987	Laboratory Testing Requirements for High Voltage Direct Current Submarine Cables (Specification 6337-LT1, Rev. 1)	Parsons Hawaii		U.S. Department of Energy
1988	Revised Basic Design Criteria Data Book	Parsons Hawaii	Krasnick, G. and J. Mansur	Hawaii Department of Business and Economic Development
1989	At-Sea Test Plan	Dillingham Construction Pacific		U.S. Department of Energy
1990	Documentation of the Support Vessel Navigation Computer Program and Fleet Management Computer Program Associated with the Hawaii Deep Water Cable Program, At-Sea Test Operations	Edward K. Noda and Associates		U.S. Department of Energy

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
1990	Equilibrium and Dynamic Analysis of the Time History Records of Cable Tension and Vessel Motion from the HDWCP At-Sea Test		Vega, L.A.	U.S. Department of Energy
1990	At-Sea Test Report	Makai Ocean Engineering, Edward K. Noda and Associates and Evans Hamilton		U.S. Department of Energy
** SUBJECT AREA: Economics				
1984	Legal, Institutional and Financial Aspects of an Inter-Island Electrical Transmission Cable	Carlsmith, Carlsmith, Wichman and Case and Prudential-Bache Securities, Inc.	Sumida, G.A. and A.L. Hills	Hawaii Department of Planning and Economic Development
1986	Commercial Cable System Cost Study (Preliminary)	Hawaiian Dredging & Construction Company	Slayton, M.T.	Hawaii Department of Planning and Economic Development
1986	Alternative Approaches to the Legal, Institutional and Financial Aspects of Developing an Inter-Island Electrical Transmission Cable System	Carlsmith, Wichman, Case, Mukai and Ichiki and First Interstate Cogeneration Capital Associates	Sumida, G.A., A.L. Hills, P.E. Lee, S.D. Suyat and R.P. Takushi	Hawaii Department of Planning and Economic Development
1987	Submarine vs Overhead Routing: A Cost Comparison for Molokai	Parsons Hawaii	Krasnick, G. and J. Mansur	Hawaii Department of Planning and Economic Development
1988	Undersea Cable to Transmit Geothermal-Generated Electrical Energy from the Island of Hawaii to Oahu: Economic Feasibility	Decision Analysts Hawaii, Inc.		Hawaii Department of Business and Economic Development
** SUBJECT AREA: Route Identification				
1982	Preliminary Route Survey Analysis	Parsons Hawaii	Hermann, F.V. and G.A. Chapman	Hawaii Department of Planning and Economic Development

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
1983	At-Sea Route Surveys	University of Hawaii, Hawaii Institute of Geophysics	Campbell, J. F.	U.S. Department of Energy
1983	At-Sea Route Survey Monitoring Reports	Sea Engineering, Inc.	Rocheleau, R. and S. Sullivan	U.S. Department of Energy
1985	Characterization of Potential Routes and Route Option Selection	The Ralph M. Parsons Co.	Krasnick, G.	U.S. Department of Energy
1985	Overland Transmission Corridor Study: Hawaii, Maui, Oahu	DHM Planners, Inc.		Hawaii Department of Planning and Economic Development
1985	At-Sea Route Surveys, Phase II-B	University of Hawaii, Hawaii Institute of Geophysics	Campbell, J. F.	Hawaii Department of Planning and Economic Development
1986	Preferred Route Analysis	Parsons Hawaii	Krasnick, G.	Hawaii Department of Planning and Economic Development
1987	Side-Scan Sonar and Swath Bathymetry Mapping Survey of the Preferred Cable Route from Maui to Oahu, Hawaii	Seafloor Surveys International, Inc.		Hawaii Department of Business and Economic Development
1988	Overland Transmission Line Corridor Study: Puna to Kohala, Island of Hawaii	DHM Planners, Inc.		Hawaii Department of Business and Economic Development
1988	Feasibility of Using Underground Electrical Cables Along Portions of the Overland Route of an Inter-Island Cable System in Hawaii	Parsons Hawaii	Krasnick, G. and J. Mansur	Hawaii Department of Business and Economic Development
1988	Visual and Photographic Survey of a Preferred Hawaii Deep Water Cable (HDWC) Route	University of Hawaii, Hawaii Undersea Research Laboratory	Malahoff, A., K.K. Zaiger, A.T. Jones and E.H. Chave	Hawaii Department of Business and Economic Development

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
** SUBJECT AREA: Environmental - Observations, Testing and Analyses				
1983	Evaluation of Expected Operational Wind, Wave and Current Conditions in the Alenuihaha Channel	Edward K. Noda and Associates	Noda, E. K.	U.S. Department of Energy
1983	Near-Shore and On-Shore Materials Characteristics	Dames & Moore		U.S. Department of Energy
1984	Deep Water Electrical Cable Corrosion Testing	Hawaii Natural Energy Institute, University of Hawaii at Manoa	Larsen-Basse, J.	Hawaii Department of Planning and Economic Development
1984	Environmental Analyses	Parsons Hawaii	Krasnick, G. and G.A. Chapman	Hawaii Department of Planning and Economic Development
1985	Waves and Near-Surface Currents in the Alenuihaha Channel	Edward K. Noda & Associates		U.S. Department of Energy
1985	Summary of Hawaii Deep Water Cable Program	Parsons Hawaii	Krasnick, G.	Hawaii Department of Planning and Economic Development
1985	Data and Observations from Submersible Dives Along the HDWC Program Preferred Submarine Route	Hawaii Undersea Research Laboratory, University of Hawaii at Manoa		Hawaii Department of Planning and Economic Development
1986	Environmental Review Plan	Parsons Hawaii	Krasnick, G.	Hawaii Department of Planning and Economic Development
1986	Bottom Roughness Survey of the Alenuihaha Channel	Makai Ocean Engineering, Inc., Edward K. Noda & Associates and Hawaii Institute of Geophysics		U.S. Department of Energy
1986	Plan for the Second Bottom Roughness Survey Cruise of the Alenuihaha Channel: June, 1986	Hawaiian Dredging & Construction, Inc.	McHale, F. and J. Van Ryzin	Hawaii Department of Planning and Economic Development

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
1986	Wind Characteristics and General Relationship Between Trade Wind Speeds and Wave Heights in the Alenuihaha Channel	Pacific Weather, Inc.		U.S. Department of Energy
1986	Cable Materials Corrosion and Abrasion Testing	Hawaii Natural Energy Institute, University of Hawaii	Larsen-Basse, J.	Hawaii Department of Planning and Economic Development
1986	Wave and Near-Surface Current Measurement Program in the Alenuihaha Channel	Edward K. Noda and Associates		U.S. Department of Energy
1986	Environmental Design Criteria for Cable Deployment Operations in the Alenuihaha Channel	Edward K. Noda and Associates		Hawaii Department of Planning and Economic Development
1986	Bottom Boundary Layer Currents in the Alenuihaha Channel	Horizon Marine, Inc.	Sanford, T.B.	Hawaii Department of Planning and Economic Development
1986	High Frequency Wave Analysis for the Alenuihaha Channel	Edward K. Noda & Associates		U.S. Department of Energy
1986	Alenuihaha Channel Current Measurements: Final Report	Horizon Marine, Inc.		Hawaii Department of Planning and Economic Development
1987	Visual Impact Analysis of Proposed 300 KVDC Line	DHM Planners, Inc.		Hawaii Department of Planning and Economic Development
1987	Kohala Slope Near-Bottom Current Measurement Program in the Alenuihaha Channel	Edward K. Noda & Associates		Hawaii Department of Planning and Economic Development
1987	Second Bottom Roughness Survey	Makai Ocean Engineering, Inc. and Scripps Institution of Oceanography		Hawaii Department of Planning and Economic Development
1987	Hydrogen Sulfide in Sediments Along the Preferred Submarine Cable Route	Parsons Hawaii	Krasnick, G.	Hawaii Department of Planning and Economic Development

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
1987	Environmental Constraints to use of a Sea Electrode in a Submarine Electrical Transmission Cable System in Hawaii	Parsons Hawaii	Krasnick, G.	Hawaii Department of Planning and Economic Development
1987	Analysis of Seafloor Surveys, Inc. Precision Bottom Data Between Maui and Oahu in Determination of a Potential Cable Route	Makai Ocean Engineering, Inc.		Hawaii Department of Planning and Economic Development
1987	Environmental Assessment	Parsons Hawaii	Krasnick, G. and J. Mansur	Hawaii Department of Planning and Economic Development
1988	Maui Slope Near-Bottom Current Measurement Program in the Alenuihaha Channel	Edward K. Noda and Associates, Inc.		Hawaii Department of Business and Economic Development
1988	Abrasion-Corrosion Studies	University of Hawaii, Department of Mechanical Engineering and Georgia Institute of Technology	Liebert, B.E., K. Htun, A. Tadjvar and J. Larsen-Basse	Hawaii Department of Business and Economic Development
1988	A Shore-based Sea Electrode System for a Submarine Electrical Transmission Cable System in Hawaii	Parsons Hawaii	Krasnick, G. and J. Mansur	Hawaii Department of Business and Economic Development
1990	Prediction of Tidal Currents in the Alenuihaha Channel, Hawaii	Hawaii Applied Research	Magaard, L., H. Loomis and L.C. Sun	U.S. Department of Energy
1990	Cable Embedment Study (2 Vols.)	R.J. Brown and Associates		U.S. Department of Energy
** SUBJECT AREA: Public Information				
1982	Program Review	Hawaiian Electric Company and Parsons Hawaii	Okura, G.N. and G.A. Chapman	Department of Planning and Economic Development
1982	Phase I Executive Summary	Hawaiian Electric Company and Parsons Hawaii	Okura, G.N. and G.A. Chapman	Hawaii Department of Planning and Economic Development

DATE	TITLE	CORPORATE AUTHOR	AUTHORS	FUNDING SOURCE
1988	The Hawaii Deep Water Cable Program: Submarine Power Cable Installation in an Adverse Environment	U.S. Department of Energy and Hawaiian Electric Company, Inc.	Eaton, R. III, and W. A. Bonnet	U.S. Department of Energy
1983	Public Informational Program	Hawaiian Electric Company and Parsons Hawaii	Shirai, S., G.N. Okura and G.A. Chapman	Hawaii Department of Planning and Economic Development
1984	Phase II-A Executive Summary	Hawaiian Electric Company and Parsons Hawaii	Okura, G.N., G.A. Chapman and G. Krasnick	Hawaii Department of Planning and Economic Development
1984	Progress Update - 1984	Parsons Hawaii	Krasnick, G.	Hawaii Department of Planning and Economic Development
1986	Phase II-B Executive Summary	Parsons Hawaii	Mansur, J. and G. Krasnick	Hawaii Department of Planning and Economic Development
1986	Assessing and Managing Potential Health and Safety Issues Related to High Voltage Direct Current Transmission Lines	Environmental Research Information, Inc.		Hawaii Department of Planning and Economic Development
1987	A Review of Hawaii Deep Water Cable Program and Geothermal Development in Hawaii	Hawaiian Electric Company, Inc.		Hawaii Department of Planning and Economic Development
1987	Phase II-C Executive Summary	Parsons Hawaii	Krasnick, G. and J. Mansur	Hawaii Department of Planning and Economic Development
1986	Public Information Program for the HDWC Program	Parsons Hawaii	Mansur, J.	Hawaii Department of Business and Economic Development
1988	HDWC Program Bibliography	Parsons Hawaii	Krasnick, G. and J. Mansur	Hawaii Department of Business and Economic Development
1988	Phase II-D Executive Summary	Parsons Hawaii	Krasnick, G. and J. Mansur	Hawaii Department of Business and Economic Development