HAWAII DEEP WATER ELECTRICAL TRANSMISSION

CABLE DEMONSTRATION PROGRAM

PHASE II

CONCEPTUAL DESIGN STUDY:

INTEGRATED CONTROL SYSTEM FOR THE HDWC CABLE LAYING

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ABSTRACT

The Hawaii Deep Water Cable Program has been established to evaluate and resolve the technical problems associated with laying a power cable from the island of Hawaii to the island of Oahu in the State of Hawaii. This cable, 250 km (150m) long, is to be laid at a maximum depth of 2135m (7000 ft) under design seas of 2.5m (8ft) and surface currents up to 1.5m/s (3kts). One of the many problems associated with this task is the integrated control system for the deployment vessel, the subject of this study.

The intent of this study is to provide a conceptual design for an integrated control system that identifies its basic method of operation, equipment required, and to determine potential problem areas. The main objective of the control system is to promptly lay the cable on the bottom, properly tensioned and properly located. In general, this is achieved by accurately measuring a variety of cable and vessel parameters, monitoring the vessel location and controlling the cable payout rate and the vessel position.

Figure 0.1 illustrates the entire control system. To the left is the information required for the overall controller. Vessel navigation information is required on the vessel position, vessel heading, vessel speed and course. Prior to sailing, the planned cable path is selected and appropriate vessel course and speed determined. The bathymetric information over the entire route is stored in the computer. During the cable lay, information relative to cable top tension, speed, total length out and complex top cable angle is measured. In addition, periodically the cable touchdown point is established with acoustic markers and/or with a remote operated vehicle. All this information is provided to a controller which computes the cable geometry behind the cable vessel.

Based on the cable geometry computed, a vessel course is determined such that the cable is being laid along the appropriate path. This information is provided to a positioning system which, in this case, is the human operator who has direct control of the propulsion units on the vessel.

A somewhat separate operation is simultaneously being performed also based on the cable geometry computation. Bottom cable tension is controlled by paying out more or less cable from the surface. Bottom cable tension can be evaluated based on

surface cable tension, top cable angles, water depth, length of cable out and vessel position. There are a variety of methods of computing bottom cable tension but none are suitable under all conditions. The conventional method is to control the top cable tension and, with knowledge of the water depth, the bottom tension is therefore controlled. In the case of the Alenuihaha Channel, however, the water depths are extreme and the static tensions at the top are high. In addition, there are large dynamic variations in the static tension at the surface making a fine resolution and response to small cable tension variations difficult. In addition, the tension method does not work while deploying down steep slopes, a condition which exists in the Hawaii Cable Program. As a result, the additional sensors are required.

Figure 0.2 is a summary of the control system selection process for the commercial Hawaiian program. The commercial program involves the laying of the entire length of cable.

For the commercial program, it is recommended that the cable laying vessel, a barge 122mx30.5m (400ftx100ft), be propelled by two rotating thrusters. These thrusters were compared to a variety of propulsion systems and proved to be both technically superior and the least expensive. Relative to control of these thrusters, a manual control has been selected guided by a computer display showing barge location and desired vessel course.

The navigation system recommended is microwave range-range with shore stations on various islands along the cable route. Accuracy is within ±3m with adequate coverage over the entire cable route.

Cable location after it leaves the vessel is the one major problem in the integrated cable control. Accurate positioning of the cable on the bottom is affected by current deflection of the cable once it leaves the vessel. In addition, currents affect bottom tensioning because of variations in the cable touchdown point depth and because of variations in cable length. Surface cable angles are the easiest obtained indicators of cable position after it leaves the vessel. For more precise location, acoustic markers are attached to given points on the cable and followed with an acoustic positioning system. Such markers are only periodically used depending upon the precision at which the cable is to be laid, the bottom slopes and the uncertainties due to a varying current.

A variety of contingency situations have been evaluated. The basic approach is to provide manual overrides in all areas possible and to provide redundancy for all critical equipment. The navigational system and overall controller, for instance, have fully operational redundant systems. The most critical contingency without a backup is the loss of one or more thruster units; the probability of such a loss is small and the cost of a backup high.

Figure 0.3 is a summary of the selection process for the HDWC demonstration program. This program has as a goal to lay a test cable in the Alenuihaha Channel, the deepest portion of the commercial route. For the most part, identical systems are recommended for this program in order that the demonstration can simulate, as nearly as possible, the actual commercial lay. Cost savings are possible by operating the demonstration program with tugs as opposed to thrusters but at a significant sacrifice in operating sea states and severe test conditions. The major difference between the recommendation for the commercial system and the demonstration program is that a remote operated vehicle (ROV) is not necessary for the demonstration unless the demonstration includes the very precise location of the cable on the bottom. Such an operation would involve an underwater ROV visually monitoring the placement of the underwater cable. At this time, the need for such precision control has not been established and awaits a bottom roughness evaluation.

In conclusion, a control system that can properly position and tension the cable for the Hawaii program is possible. Most of the components for the system are commercially available with the exception of the surface cable angle measurement. The cable lay and control will involve added complexities because of the depth, cable dynamics, path width and bottom slopes; these should be tested in the HDWC demonstration program.

ACKNOWLEDGEMENTS

The work performed in Chapter 7 on vessel propulsion has been done by Dr. Luis Vega and Associates. Chapter 5 on Cable locating instrumentation has been written with the assistance of Mike Mullin at Oceaneering, Inc. in Houston, Texas. Chapter 6 on navigation was written with the assistance of Ian Sandison of Hawaiian Dredging & Construction.

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CHAPTER 1

INTRODUCTION

This chapter provides background information for the Hawaiian Interisland cable Program and describes the role that this study plays. The objectives of the integrated cable laying control system are described together with conventional solutions in the industry to similar problems.

1.1 HAWAIIAN INTERISLAND CABLE PROGRAM

The island of Hawaii in the State of Hawaii is rich in geothermal energy, however it is 250 km (150 mi) from the main population center of Oahu. The Hawaii Deep Water Cable (HDWC) Program, funded by the Department of Energy and the State of Hawaii, is investigating the potential of laying electrical power cables between the two islands as part of an electric power transmission system. The technical obstacles are formidable: the water depths between the islands approach 2000 m (6300 ft), the seas are very rough, and the cable lengths are long. A cable lay in these waters would involve an operation in depths four times greater and in seas three times greater than the current state of the art.

There is discussion throughout this report on both the commercial cable system and the HDWC demonstration program. The commercial system is the final operating system composed of three power cables and a ground return laid over the entire 250 km distance. In contrast, the HDWC program has as its purpose the study and the demonstration of solutions to the difficult engineering problems associated with establishing the commercial system. One of the major goals of the HDWC program is to lay a test cable under commercial system conditions in the Alenuihaha Channel between Hawaii and Maui, the deepest portion of the commercial route. This HDWC At-Sea Demonstration Program involves the laying of approximately 9150 m (30,000 ft) of cable.

Both the commercial and the HDWC demonstration program are studied in this report. The problems in the commercial system need to be identified such that they can be properly studied and demonstrated, if necessary, in the HDWC program.

1.2 INTENT OF THIS STUDY

The intent of this study is as follows:

- o Provide a conceptual design of the integrated control system A variety of installation control methods will be evaluated and one or more methods selected which provide appropriate solutions for cable laying control
- o Provide coordination to component design The integrated control system involves cable handling

these parameters, accurate computation is made to determine the present situation and commands are sent to the cable handling subsystem (CHSS) which handles the overboarding cable and the vessel propulsion system. The entire integrated control system is illustrated as a block diagram in Figure 1.1. On the left of this figure are the various sensors and known information onboard the vessel. Navigational information is collected; the planned cable course is known, including detailed bathymetry along the route; sensors at the top of the cable measure tension, speed, length out and the upper cable angle plus the cable touchdown is monitored in a variety of ways. This information goes into an onboard controller which can compute the cable geometry and loads behind the vessel. On the basis of this, commands go out to either the propulsion units controlling the vessel or the CHSS tensioning system. All of these blocks are not necessarily machines; some can be human operators. The chapters throughout this report emphasize various portions of this diagram.

1.4 CONVENTIONAL SOLUTIONS

In laying power cable, the vessel position and therefore the bottom cable position is normally controlled by mooring a vessel and winching it across the body of water or by dynamically positioning the vessel with some form of propulsion. In shallow water, high current situations, the mooring system is normally used and in deeper water the propulsion methods are used. Examples of moored cable laying is the Hong Kong and Northumberland Strait deployments and an example of the dynamic positioning laying would be the Pirelli cable lay to Sicily in 305 m (1000ft) of water or the connection of the main island of Honshu in Japan to Hokkaido by Sumotomo, also in 305 m (1000 ft) of water.

The proper tensioning of cable on the bottom is conventionally achieved by knowing the depth of water and maintaining a corresponding tension at the surface with a tensioning machine. As the vessel moves, cable tension increases and the tensioning machine pays out more cable. For power cable, the cable is laid under tension on the bottom to avoid any possibility of kinks.

Communication cable, however, is laid quite differently. Communication cable is not normally laid on the bottom under tension because of the desire to avoid any freespan on the bottom (which the unarmored cable cannot accommodate) and to allow slack for repair. Excess cable (greater than the path length) is laid resulting in a zero bottom tension. Such a laying technique requires precise navigation of the laying vessel and this is normally achieved by paying out a small steel taut wire in conjunction with the communications cable. The length of taut wire deployed is precisely measured and its rate of payout governs the communications payout speed.

1.5 FACTORS UNIQUE TO THIS PROGRAM

There are five factors which are unique to this program and which directly influence its integrated control system. The great water depth, steep bottom slopes, the potentially rough sea bottom, the high sea states and strong currents all present challenges to the integrated control system.

The greatest depth of water is 2135 m (7000 ft) in the Alenuihaha Channel between Maui and Hawaii. This depth represents a depth four times greater than the current state of the art in deploying power cables. Because of this depth and the weight of the cable, surface tension can be very high. Figure 1.2 illustrates a typical cable catenary being deployed behind the surface vessel. Normally observed is a surface cable tension, T, the top cable angle, A, the length of cable deployed, S, and the depth of water, D. Unknown is normally the touchdown point and the bottom tension in the cable, B. There is a basic relationship between the depth of water, the weight of the cable and the tensions at the top and bottom, as illustrated in Figure 1.2. If the tension at the top is known, the tension at the bottom can normally be computed. Because of the great depth in the Alenuihaha channel, the static tension is rather large and and the tension at the bottom could sometimes be obscured, particularly when considering cable dynamics. Properly laying a cable with a bottom tension accuracy of 900 kg (2000 lbs) can be difficult when monitoring an upper static tension of 57000 kg (126,000 lbs) with dynamic loads superimposed of up to 30%. Typical parameters for laying a cable in the Alenuihahà Channel are as follows:

Cable wet weight	24.9 kg/m	16.7 lb/ft
Water Depth	2135 m	7000 ft
Bottom cable Tension	4000 kg	9000 lbs
Top Cable Tension	57,000 kg	126,000 lbs
Touchdown behind vessel	1000 m	3400 ft
Vessel Speed	1 m/s	2 KTS
Top Tension Dynamics	± 30%	± 30%
Top Cable Angle	20^{o}	20^{o}

Steep slopes on the bottom can present particularly challenging control problems because the touchdown point may not be well defined. This can obscure the computations for the cable shape and bottom cable tension. Slopes exceeding 20 degrees can occur both in the direction of the cable and perpendicular to the cable lay.

While the bottom has not been thoroughly surveyed, the volcanic nature of the islands suggests the possibility of a rather rough bottom. This may require a high accuracy placement of the power cable in deep water. The sea conditions in the

Alenuihaha Channel also pose an unprecedented challenge to the control system. Seas as high as 2.4 m (8 ft) or less occur 75% of the time in the channel. These rough seas impose significant dynamic loads on the cable and challenge the maneuvering and positioning ability of the vessel. In addition, high surface currents 1.5m/s (3kts) present the single largest load on the cable laying vessel.

CHAPTER 2

CABLE LAYING CONDITIONS AND ENVIRONMENT

To analyze, design and specify a cable laying control system a baseline must be set that establishes relevant cable characteristics, cable laying vessel characteristics and environmental conditions. The latter includes bathymetry, sea floor slopes, currents, wave conditions and weather. The intent of this chapter is to describe these baseline characteristics and conditions and discuss both typical and worst case situations.

2.1 CABLE

The commercial cable lay between the islands of Hawaii and Oahu will include three cables (two plus a spare) and a metallic return cable. The approximate length of each cable will be 250 km (155 mi), dependent on the cable route selected. This is in comparison to the HDWC, demonstration cable lay of approximately 9 km (6 mi). The cable selected as a baseline for this study is self contained, oil filled, #116, (draft cable construction specification) with the following weights:

Dry	36.4 kg/m	(24.4 lb/ft)
Wet	27.0 kg/m	(18.2 lb/ft)

It is 119.5 mm (4.705 in) in diameter, and can withstand a maximum tension of 78.7 mt (173,000 lbs).

2.2 CABLE LAYING VESSEL

In a previous study (Ref Makai Ocean Engineering and Vega and Associates "Cable/Barge System Response During Test Laying Operations in the Alenuihaha Channel", March, 1984) it was concluded that there are no existing cable laying vessels with the equipment required for handling the proposed power cable. Therefore, various sizes of generic barges were analyzed, and the 122x30.5 m (400x100 ft) barge earlier analyzed was selected as both a likely commercial and test vessel; it is used in this study.

2.3 CABLE PATH

2.3.1 CURRENT CABLE PATHS

Three cable routes have been identified by Parsons Hawaii as the highest potential candidates for a commercial cable connection between Hawaii and Oahu. These routes are plotted in Figures 2.1, 2.2, and 2.3 to illustrate only the general path followed by the cable between islands. A table of approximate cable lengths for each segment of the paths is presented in Figure 2-4.

PROPOSED CABLE ROUTE
OPTION NUMBER I

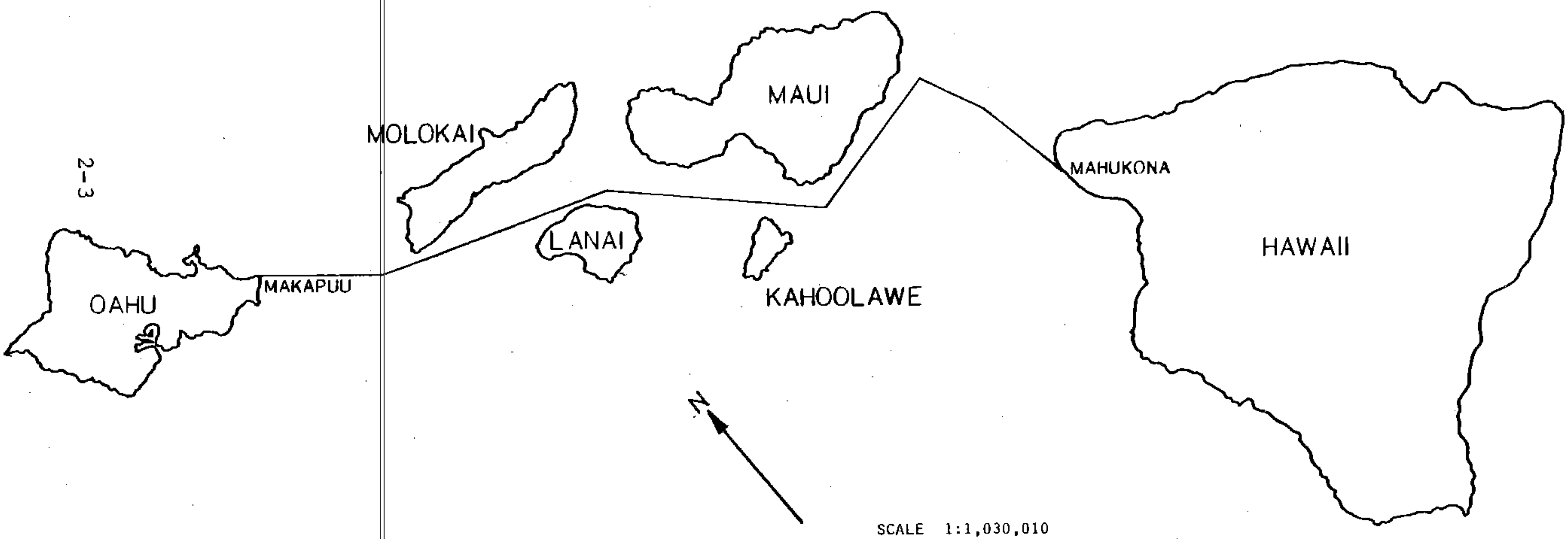


FIGURE 2.1

PROPOSED CABLE ROUTE
OPTION NUMBER 3

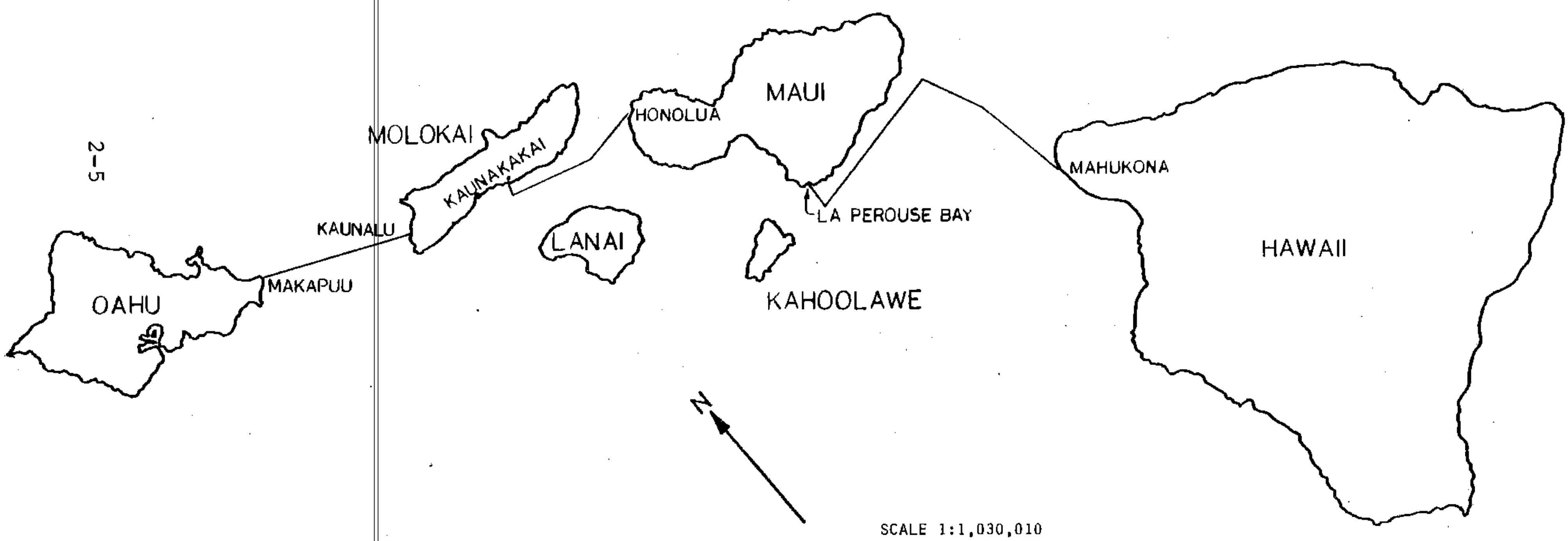


FIGURE 2.3

DEPTH AND SLOPE PROFILES FOR ROUTE OPTION I

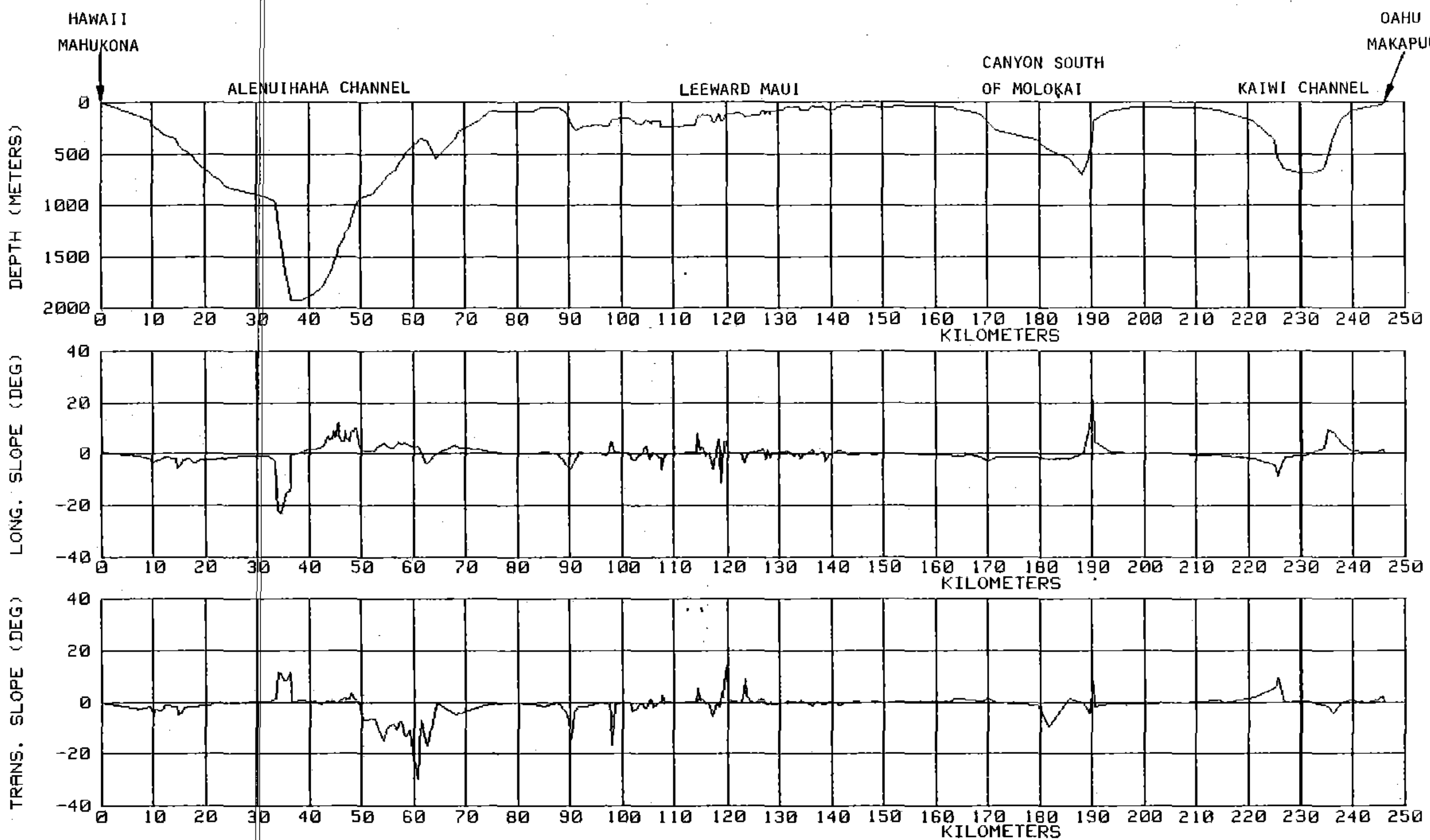


FIGURE 2.5

DEPTH AND SLOPE PROFILES FOR ROUTE OPTION 3

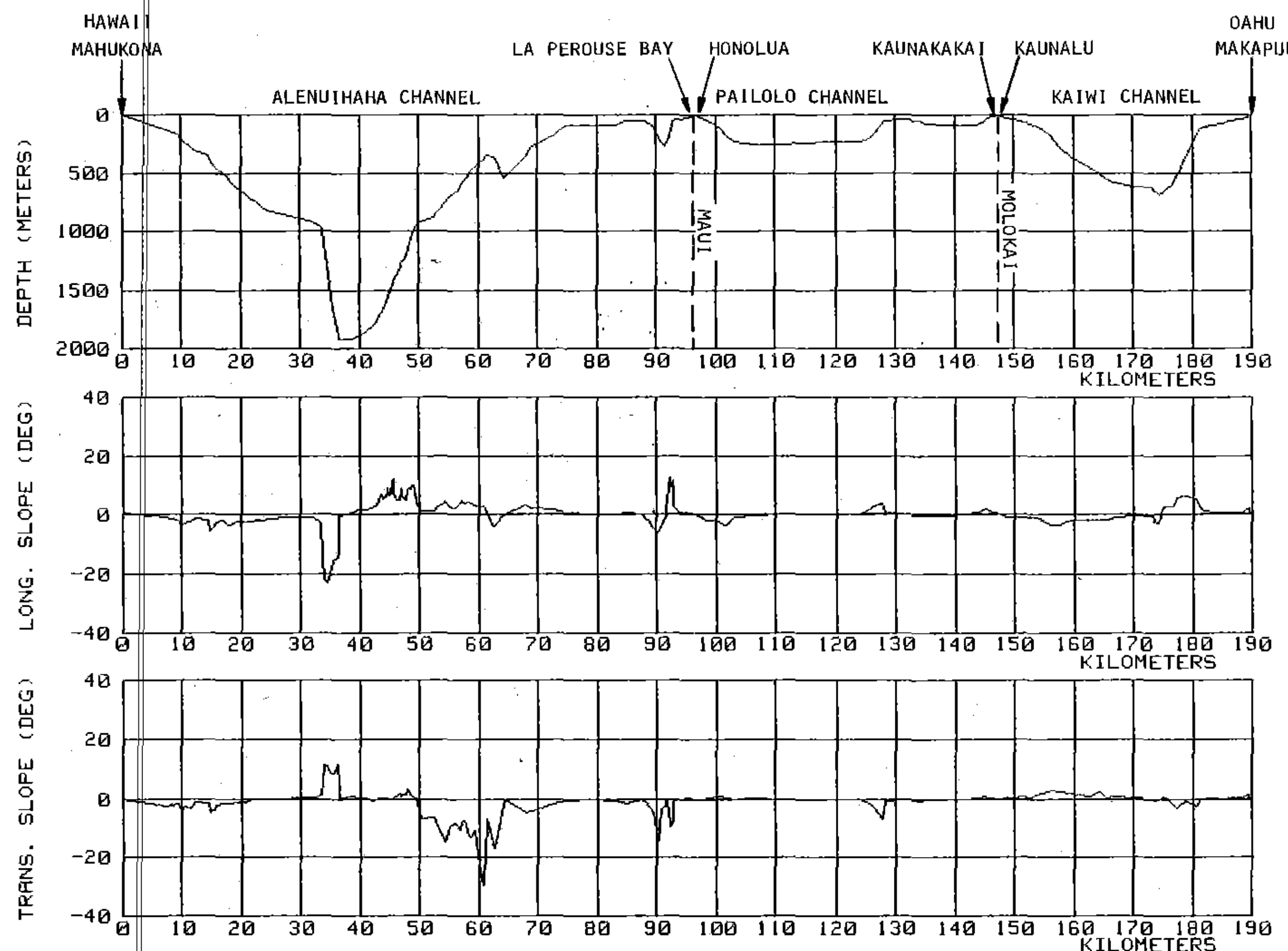


FIGURE 2.7

WATER DEPTHS BETWEEN THE HAWAIIAN ISLANDS

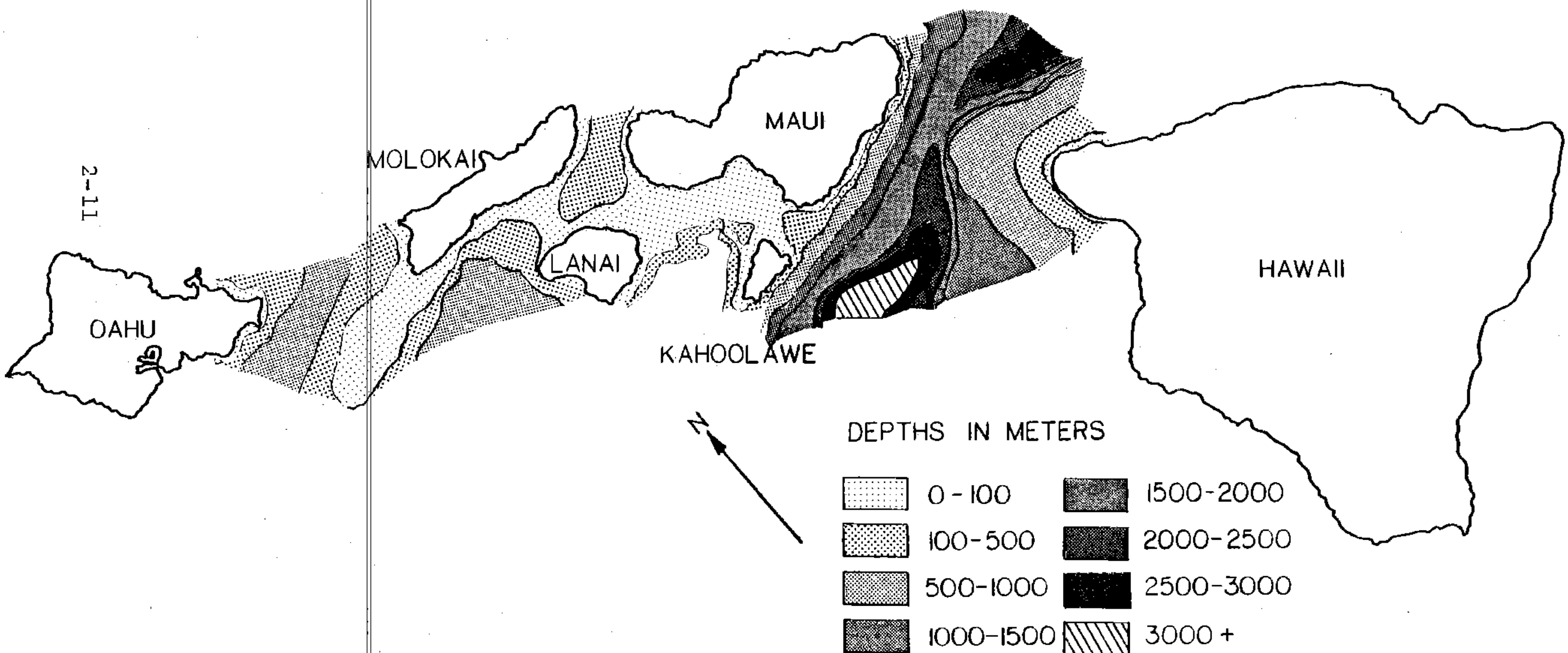
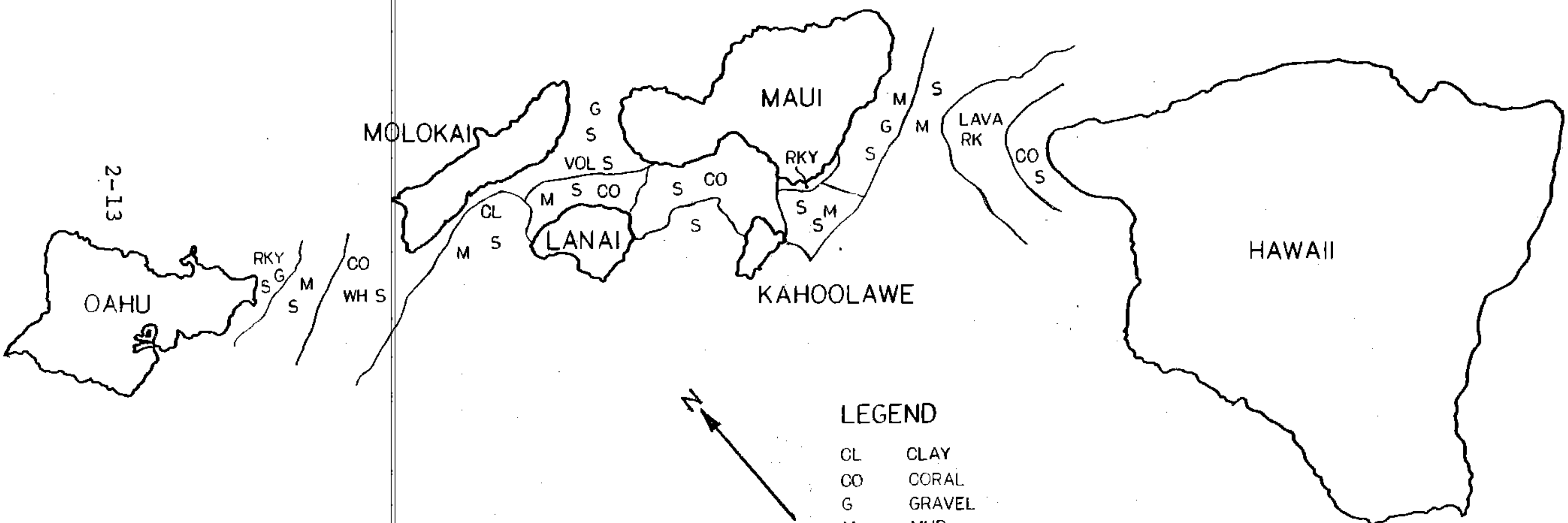


FIGURE 2.9

GENERAL SEA FLOOR CHARACTERISTICS BETWEEN THE HAWAIIAN ISLANDS



SEA FLOOR CHARACTERISTICS SHOWN ARE EXCERPTED FROM NOAA NAVIGATIONAL CHARTS AND ARE INTENDED TO INDICATE ONLY <u>GENERAL</u> BOTTOM CONDITIONS.

FIGURE 2.11

2.3.4 FUTURE CABLE PATH BATHYMETRY

Prior to a commercial cable lay, bathymetric data collection should be conducted that would yield the position and depth of significant bottom features. Bottom "roughness" needs to be identified in order to determine the required bottom cable laying tolerance. Such accurate bathymetric surveys will probably imply picking an approximate cable path prior to data collection so that survey efforts can be concentrated within smaller areas.

2.4 WEATHER

The cable laying control vessel must be equipped to withstand and maintain its position and heading against the wind, wave and current loads experienced along the cable path. Surface currents have been identified as the major load component on the cable laying vessel (Chapter 7). Therefore, accurate knowledge of the environmental conditions along the cable route is most important to the control system design. Concise information on wind, current and wave conditions for different channels and waterways along the proposed cable paths has not been compiled; information on the Alenuihaha Channel is now being collected for the HDWC Program. Studies of conditions in localized regions during a given season have been commissioned for a variety of projects. Collecting and compiling weather data from such sources were not carried out for this study.

2.4.1 ALENUIHAHA CHANNEL

A report on the major oceanographic and meteorological factors in the Alenuihaha Channel which would influence the conceptual design of a cable laying vessel for the HDWC was carried out by E.K. Noda and Associates. Noda's results are tabulated in Figure 2.12. The following is a summary of the wind, wave and current conditions in the Alenuihaha Channel.

A. Wind

Channel winds are primarily trade winds from the northeast or east and are 18 m/s (35 kts) or less 75% of the time.

B. Currents

The estimated direction of the extreme 1.5 m/s (2.9 kt) currents as well as subsurface currents is to the northeast through the channel.

C. Waves

Sea waves are generated by the strong and gusty northeast to east tradewinds. The significant wave height is 2.4 m (8.0 ft) or less 71% of the time and the significant wave period is 6.1 s. Swell waves are primarily from the south and southwest with a significant wave height of 1.2 m (4.0 ft) and period of 13 s.

2.4.2 THE REST OF THE CABLE PATH

It is generally acknowledged that the channels between islands are areas which are subjected to the most severe winds, waves and currents along the cable path. Among these channels the Alenuihaha is considered the most severe due to the high mountains on either side that accelerate winds through the channel and which in turn generate high sea waves. The southern exposure of the channel makes it vulnerable to swells from the south. It is probable that wind and wave conditions in other channels along the cable path will fall within the baseline conditions reported by Noda in Figure 2.12. Therefore, without better data on weather conditions in the channels along the cable paths, the magnitudes reported in Figure 2.12 will be considered to apply to all channel areas.

2.4.3 WORST CURRENT CONDITIONS

Large surface and subsurface currents have a major impact on final cable position on the ocean floor: Surface currents are the most important load imposed by the environment on the cable laying vessel. Subsurface currents deflect the suspended cable and alter its final position proportionally. The latter effect increases with water depth.

Due to the high currents and deep water in the Alenuihaha Channel, worst case currents will occur in this area. Since our knowledge of the direction of these currents is limited, the cable laying vessel and control system should be designed to withstand the maximum current, 1.5 m/s (2.94 kts), both parallel or perpendicular to the cable path.

2.5 WORST COMBINATION OF CONDITIONS

The worst combination of bathymetric and environmental conditions along the proposed cable routes will occur in the Alenuihaha Channel. Steep submarine slopes of up to 35o occur at extremely deep depths, 1000-2000 m (3280-6560 ft), where surface and subsurface currents are as great as any experienced in the Hawaiian Islands. High wind and wave conditions could easily arise in the channel especially if the cable laying operation extends for some duration. No other area along any of the proposed routes presents such a combination of conditions.

2.6 TYPICAL COMBINATION OF CONDITIONS

The majority (60%) of cable route options 1 and 2 are in waters less than 250m (820 ft) deep. These shallow waters are

CHAPTER 3

CABLE LAYING STATICS AND CONTROL CRITERIA

This chapter outlines the criteria for the integrated control system; it details what is to be achieved and the required accuracy. In order to fully understand the cable laying control problem, the cable laying statics are reviewed and a basic approach to the control problem is developed.

3.1 CONTROL CRITERIA

The integrated control system basically has three goals:

- Properly position the cable along the desired bottom path.
- Lay the cable on the bottom under the proper tension.
- Minimize cable tensions at the surface by optimal positioning of the cable laying vessel.

The means to achieving these goals is through proper positioning of the vessel on the surface and proper payout of the cable from the vessel. Reference should be made to Figure 1.1.

3.1.1 CABLE POSITIONING ON THE BOTTOM

The required cable laying accuracy on the bottom is a function of the width of the bottom survey cable path and a function of the number of cables which are being laid down that path. Bottom roughness and other obstacles determine the available path width on the bottom. Depending upon the number of paths available, one or more cables may be laid down a single path. These cables cannot cross one another and, in some areas, they may have to be sufficiently spaced to accommodate the repair methods appropriate for that particular depth. In shallow water, the state of the art in repair would call for spacing between the cables equal to the water depth to allow for re-laying the repair bight. In the case of the very deep waters of the Alenuihaha Channel, re-laying a bight is beyond the state of the art and it is not anticipated that this repair technique would be utilized and therefore the spacing requirement would not be necessary. If bottom conditions were not a limiting factor in the path selection, the cable would be laid with a large distance between to minimize probability of mutual failure. In the case of severe path restrictions because of bottom conditions, it may be required

Cable tension on the bottom is desirable because the small tension insures that the cable is straight and cannot be kinked on the bottom. If excess cable is placed on the bottom with zero tension, a coil could occur in the cable on the bottom which, with subsequent pulls by the surface vessel, would close and cause a kink thereby damaging the cable.

3.1.3 VESSEL POSITION, VESSEL HEADING AND SPEED

The vessel position, controlled by the thrusters, determines whether the cable is laid to the left or right of the desired cable path. Since the ultimate goal is to accurately lay the cable on the bottom, the same tolerance for bottom cable position will minimally apply to the surface vessel. There is, however, an additional error in relating surface vessel position to bottom cable position; this error is in the cable offset due to cross ocean currents. Vessel positioning control is dependent upon bottom cable tolerance and cable offset due to cross currents.

There are restrictions on vessel heading imposed by the cable handling equipment. The overboarding sheave is not free to swivel like a true fairlead, its axle is fixed. The cable can therefore be deflected out of the plane of the overboarding sheave at the point where it leaves the sheave. This angle (beta) should not exceed 10° in order to not overbend the power cable. Figure 3.1 illustrates the restriction on the vessel heading due to this 10° and less angular restriction. Note that beta is caused by vessel roll, cable deflection by currents or turning (yaw) of the vessel. For a practical level in 7000 ft of water, the cable angle (alpha) may be approximately 70° from the horizontal and therefore the vessel restriction (gamma) would be $\pm 30^{\circ}$. The angle beta includes roll, so with a roll of $\pm 5^{\circ}$, beta is further restricted to 5° and gamma limited to $\pm 15^{\circ}$. The worst case would occur in shallow water with alpha dereasing to 60°, rolling at $\pm 5^{\circ}$, and vessel heading limited to $\pm 10^{\circ}$. Under limited heading variations, it may be difficult to limit roll.

Vessel heading is also a function of sea state and currents. Large broadside currents impose high loads on the vessel and these are desirable to minimize. In addition, broadside seas cause the worst heave motion at the stern of the vessel and result in the largest dynamic loads. Particularly in the case when the CHSS is not functioning, the vessel should maintain a position relative to the waves to attempt to minimize the dynamic loads on the cable.

3.2 CABLE STATICS

The integrated controls system deals primarily with very low frequencies. Higher frequency events such as cable dynamics caused by waves and cable vibrations are dealt with in the cable handling subsystem. The primary concern with the overall control system is the quasi-static solution of the cable behind the cable vessel and moving from one static solution to another. These events occur slowly.

The basic relationship between bottom and top tension and depth of water has been presented in Figure 1.1. The tension on the top is equal to the touchdown depth times the wet weight of the cable plus any bottom tension at the touchdown point. This is a very basic relationship that has been used for many years in cable laying; it is independent of cable angle and currents. To lay a cable at a given tension on the bottom, one needs to know only the bottom depth to compute the desired tension at the surface. This tension at the surface is maintained with a constant tension machine.

Tension control is not the only means of laying cable. By knowing the exact position of the vessel, the depth of water, the amount of cable paid out and the vessel speed, the total geometry could be computed to a unique solution which could have only one bottom tension. In some cases, it may be easier and more precise to measure cable length than to measure top cable tension. Figure 3.2 illustrates the relationship between cable length and bottom tension. At 2135m (7000 ft), an error of 2000 kgs (4500lbs) in our normal 4000kg (9000 lb) bottom tension corresponds to a cable length variation of 60m (200ft). When laying cable at 2135m , it may be easier to control the cable length within 60m as opposed to controlling the top cable tension within 2000 kg of the total static load of 57,000 kg with ±30% dynamics.

There is also a relationship between bottom tension and top cable angle. The larger the bottom tension the more the cable is pulled behind the vessel and the shallower the cable angle. Figure 3.3 illustrates the relationship between bottom tension and top cable angle for cable laying depths of 2135m (7000ft) and 500m (1600ft) depths. At shallow cable laying depths, the top cable angle is a better indicator that at 2135m (7000ft) where one would have to have a very fine cable angle resolution to measure tension by cable angle; 1^{o} = 2000kg bottom tension variation..

The relationships shown in Figure 3.2 and 3.3 are also a function of vessel speed. As the vessel moves faster through the water, the cable strains further behind the vessel and the top cable angle changes. The relationship between top bottom tension and bottom tension does not change but if one is laying cable by measuring precisely the position of the vessel, the depth of the water and the length of the cable deployed, the vessel speed must be taken into account. Figure 3.4 is a plot of vessel speed versus cable length for a bottom tension of 4000kg and a given vessel position on the surface. The plot shows that a vessel operating in 2135m of water at 1 m/s should have laid out out 250m less cable than for the same vessel in the same position but laying cable at 0.5 m/s. If measurement accuracies are to be

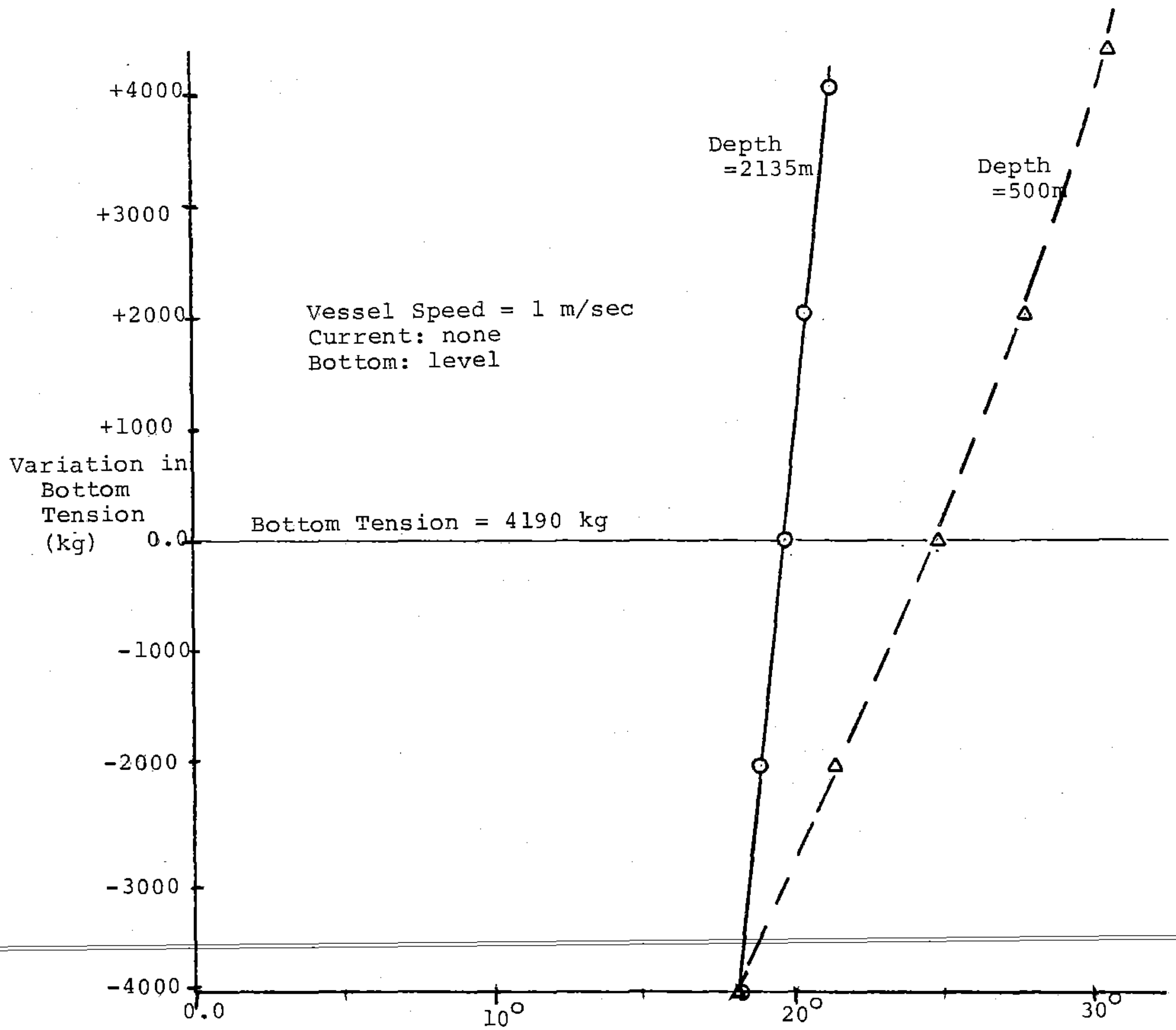


Figure 3.3 Bottom Cable Tension vs. Top Cable Angle at 500m and 2135m Depths

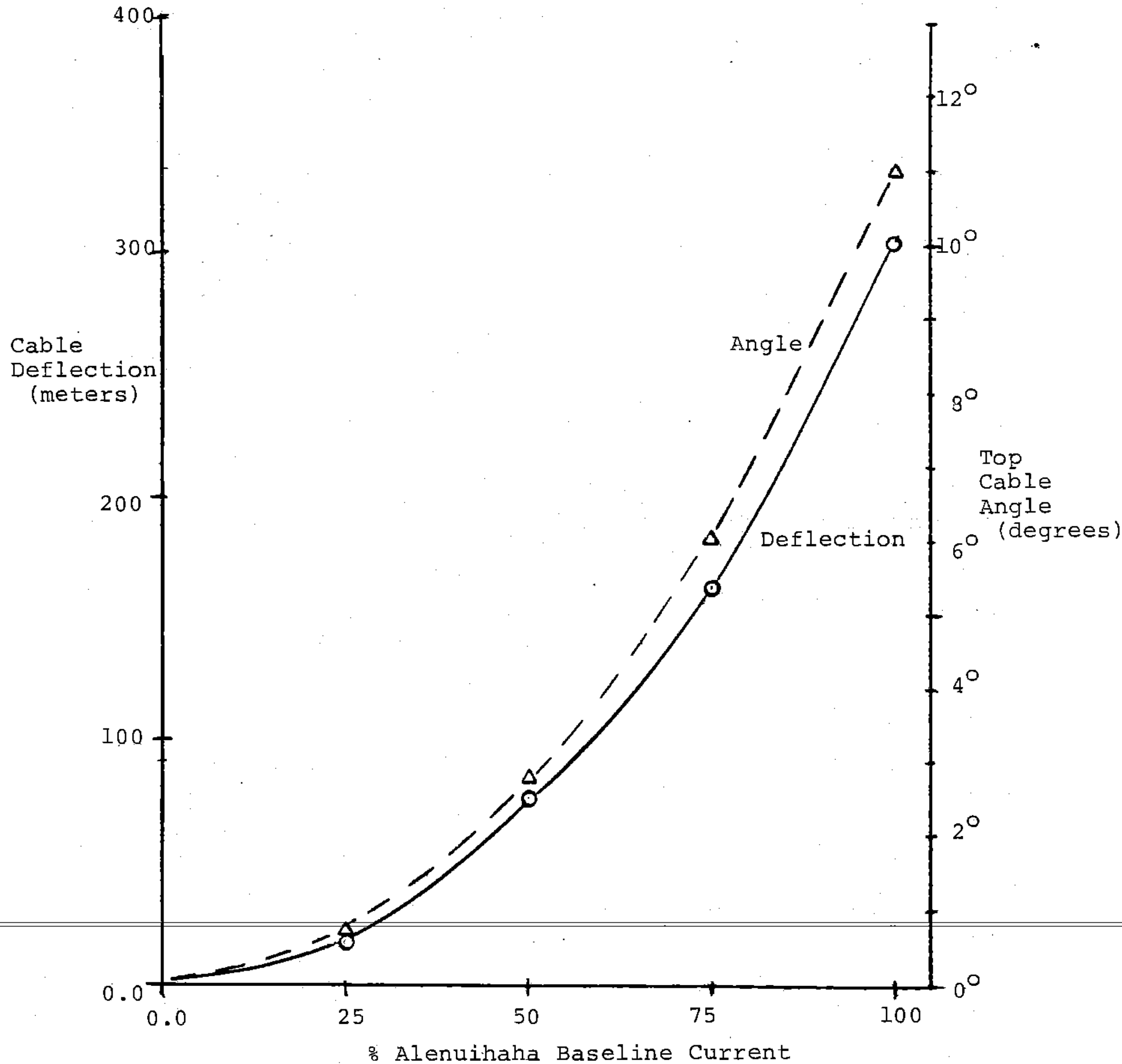


Figure 3.5 Side Deflection of Cable and Top Cable Angle as a Function of Cross Current

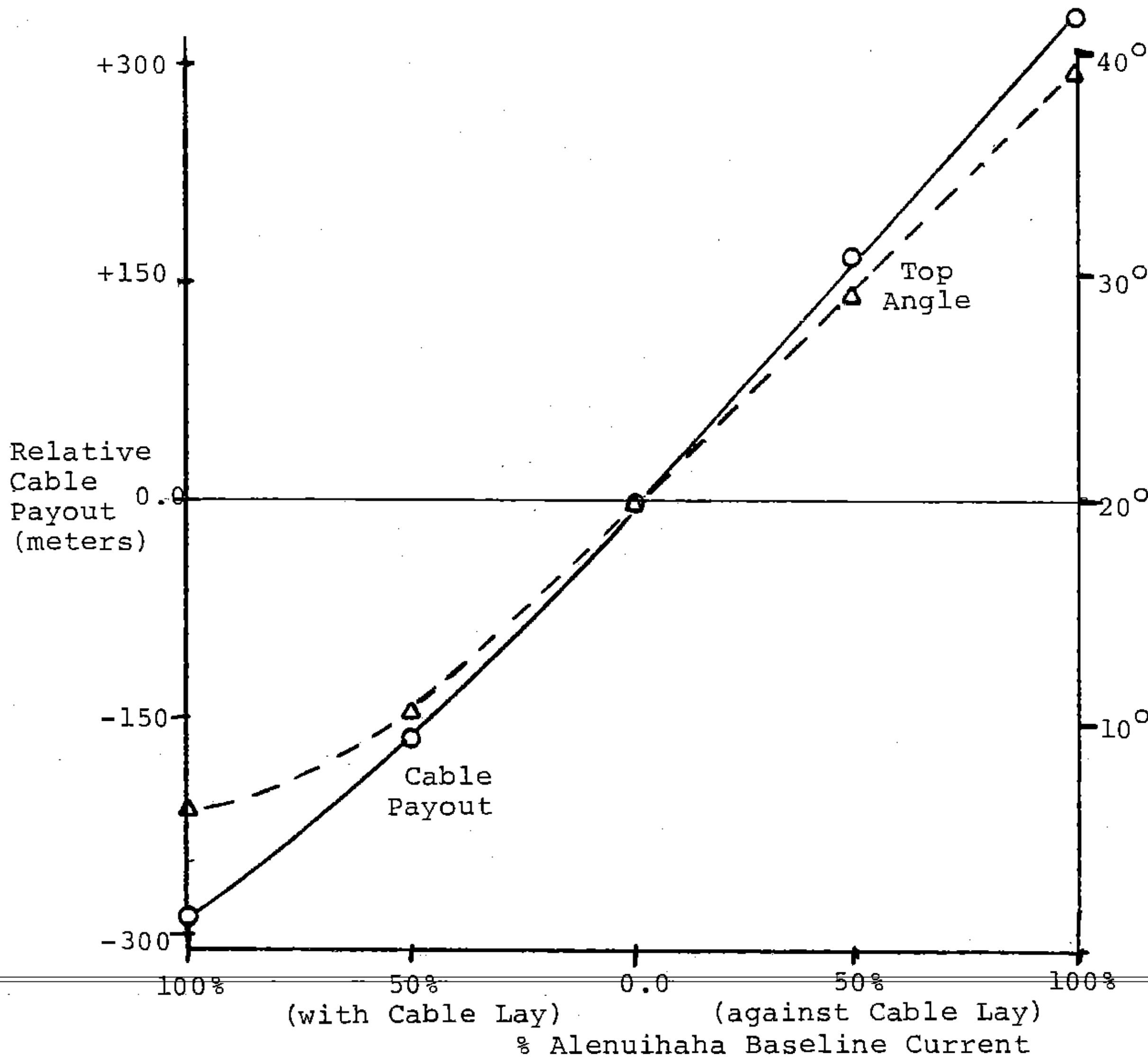


Figure 3.6 Relative Cable Payout Length and Top Cable Angle at 1 m/sec Speed vs. Current into and with Cable Lay Direction

maintained to within 60m, speed is a critical concern and must be measured to within 2% - easily achievable for a precise navigation system over several minuites of averaging.

Currents also affect the static shape and tensions in the cable being laid. One of the major problems is accurately placing cable on the bottom and the only error factor in deflecting the cable either to the left or right of the vessel path is cross currents. Figure 3.5 illustrates the top angular deflection to the right or left of the cable path and the resulting deflection
at the touchdown point for various cross-current intensities.

3.4 BASIC CONTROL SYSTEM

The following is a general discussion of the control system relative to the control criteria and statics discussed above. further details are provided in following chapters.

3.4.1 CABLE TENSION

There are three possible ways in which to control the cable tension on the bottom:

- Tension Method: If the touchdown depth and the weight of the cable is known, the bottom tension is controlled by closely controlling the top tension.
- Length Method: If the depth, cable route, cable starting point and vessel speed are known, the tension at the bottom can be controlled by closely monitoring the length of the cable paid out from the vessel.
- Angle Method: If the depth, currents, vessel speed, and cable weight are known, the bottom cable tension can be controlled by carefully monitoring the surface cable angle.

Of the three methods, the tension method is the most straightforward and has been used extensively in the past in laying cable. It works extremely well in relatively shallow water where the tension at the bottom is a significant component of the tension at the top and cable dynamics are not large. In cases of going down steep slopes, in very deep water with high tensions on the surface and under conditions of large dynamic components; the tension method does not do well. The angle method is valuable as a backup or confirming indicator but is not suitable for bottom tension control; the surface cable angle variations are too small to reliably measure,

TABLE 3.1 SYSTEM REQUIREMENTS

Systems Involved	Objectives of Overall Control System: Bottom Cable Position	Bottom Cable Tension	Optimum top Cable Handling	Overall Need
Control				
Vessel Control				
Position	C	C		C
Heading	S		C	C
Velocity				
Magnitude		C		C
Direction	C	C		C
CHSS Control				
Tension		C		C
Speed		C		C
Sensors				
Navigation				
Position	C	C		C
Heading	S		C	C
Velocity				
Magnitude		C		C
Direction	C	C		C
Cable				
Position on bottom	C	C		C
Angle at top				
Rel to vertical	S	S	C	C
Rel to North	S	S	C	C
Top tension		C		C
Speed rel to vessel		C		C
Vessel				
Thruster status	C		C	C
Vessel heave			S	S
Environment				
Waves				
height			S	S
direction			S	S
Current				
magnitude-profile	S	S	S	S
direction-profile	S	S	S	S
magnitude-surface	C	C	S	C
direction-surface	C	C	S	C
Bathymetry	C			C

C: Critical need
S: Secondary need

SECTION 4

BOTTOM CABLE TENSION CONTROL

Bottom cable tension is controlled through the cable handling equipment and various methods have been presented in Chapter 3:

- <u>Tension method</u>: Control the bottom tension by monitoring the surface tension.
- <u>Length method</u>: Control bottom tension by monitoring the length of cable paid out.
- <u>Angle method</u>: Control bottom tension by monitoring the surface cable angle.

Each of these methods will be discussed in more detail in this chapter. A description of the cable handling equipment and the required low frequency control of that equipment is given.

4.1 DESCRIPTION OF THE CABLE HANDLING SUBSYSTEM

Western Gear in Everett Washington has been conducting a conceptual design on the cable handling subsystem (CHSS). This system consists of a turntable for cable storage, a linear tensioning machine for holding and powering the cable over the side and an overboarding sheave for guiding the cable off the end of the vessel.

The linear tensioning machine is the primary component of concern to the integrated control system. It is a long hydraulic track-type tension system capable of holding back on the cable and maintaining near constant tension. Output cable tension is measured by the machine and compared to a command tension provided by the operator. If the output tension is too low, the machine brings in cable; if the output tension is too high, the machine lets out cable. The normal method of operating this machine is on the constant tension mode however it can also operate on a constant speed mode.

One of the primary advantages of the linear tensioning machine is that it has the ability to act as a heave compensator, thus alleviating some of the high dynamic tensions in the cable. Its fast response rate allows it to follow cable tension oscillations as high as one and two radians per second. This constant tensioning feedback control loop is internal to the CHSS and is not part of the integrated control system,. The integrated control system operates at much lower frequencies; control of cable dynamics is not one of its objectives.

The CHSS measures the cable overboarding tension with a tensioning table and this information is provided to the integrated control system. The full scale of this table is presently at 76,000kg (84 tons) with an accuracy of 1% of full scale. At less than 15% of full scale the accuracy drops to 3.5% or 2700kg (3 tons). Approximately another 1% is lost in the stern sheave. Overall instantaneous uncertainty would be less than 1500 kg in deep water.

The speed of the CHSS machinery is presently limited by power to the turntable and the ability to accelerate and decelerate the turntable. The current maximum speed of the Western Gear design is 1m/s (2kts) although higher speeds may be desirable.

The CHSS machinery also measures cable length with a meter wheel system. Cable length measurement is limited to 2% accuracy. Considerably better measurement can be made of the entire cable length by updating the overall cable length measurement with manufacturer's marks on the cable at every kilometer, minimum. The overall length measurement would then be limited to 2% of 1 km or 20 m. A higher accuracy would be desirable.

The linear tensioning machine can be operated in either a speed mode or a tension mode. In the speed mode a constant speed is maintained by the machine and no heave compensation is possible. In the tension mode the machine attempts to maintain a constant tension in the cable. This is done with a feedback loop where the measured cable tension is compared to the command tension and this tension differential causes the machine to either payout or haul in cable. Response times are fast; the system responds quickly to large tension variations in the cable due to dynamics.

4.2 CABLE BEHAVIOR

The cable suspended below the vessel has characteristics which differ depending upon the frequency of excitation. At an ocean wave frequency and higher, the cable appears very stiff because of the large mass and stiff elasticity of the cable itself. Cable stiffness at these high frequencies could be anywhere from 2600 to 8800 N/cm (1500-5000 lb/in). If, however, the cable is pulled very slowly, the entire geometry of the cable changes and there is a geometrical stiffness which is considerably less. At a 2135m (7000ft) depth, this geometric stiffness could be as low as 2.6 N/cm (1.5 lb/in) (Figure 3.2). The wide range of "stiffnesses" given here illustrate a fundamental problem with bottom cable tension control. If the linear tensioning machine is designed to respond to the higher cable stiffness in order to act as a heave compensator, it may not respond well to the geometrical changes in cable shape.

4.3 CABLE BOTTOM TENSION CONTROL METHODS

In the following paragraphs three bottom cable tension control methods are discussed: tension, length and angle.

4.3.1 TENSION METHOD

The basics for the tension method of bottom cable tension control were presented and illustrated in Chapter 3. Bottom cable tension is computed by knowing the top cable tension and subtracting the depth of the touchdown point times the weight of the cable in water. For the linear tensioning machine, the control tension can easily be computed and set on the machine.

There are several conditions under which this control method is not suitable. Under some circumstances, the depth of the touchdown point is not known. This may be the case when laying the cable parallel to the contours on a steep slope. A side deflection of 300 m (1000 ft) results in a touchdown depth variation of 109 m (358 ft) and a corresponding bottom tension differential of 2700 kg (6000 lb). This is a significant error in maintaining the desired bottom tension.

In laying the cable down steep slopes, as shown previously in Figure 3.7, there is no variation in surface cable tension as a function of cable length out. Bottom tension, however, does vary as a function of cable length out. It is therefore impossible to maintain a constant bottom tension by monitoring the surface tension only under these conditions.

One additional problem with the tension method is the actual measurement accuracy of the tension on the vessel. Static tensions are as high as 57,000 kg (126,000 lb) ± 30% for dynamics. The tension method would require measuring the static cable top tension by averaging with a dynamic measurement system that has a 1500 kg overall accuracy. The desired accuracy is tentatively 2000 kg to assure the bottom tension is always greater than 0; the requirement could be lower in some areas of rough bottom. There are additional errors in touchdown depth and slope.

The tension method requires that the linear tension machine pays out cable in response to a slowly increasing tension seen at the surface due to geometric changes in the cable hanging below. As shown previously, this tension increase is rather slow and the machine has been tuned to operate best in the dynamics of very large tension variations. It is not known at this time how well it would respond to a rather weak signal.

During the HDWC demonstration program, the cable starting end must be lowered into deep water over the side and retrieved in the same way. This cannot be done with the tensioning machine operating on a tension mode; the cable weight and tension increase with depth and the machine tends to dump out cable faster and faster (to its limit) in response to this increase. The heave compensation capability would be lost, particularly when it may be needed during cautious vertical recovery of the cable in rough seas after a successful deployment

The tension method does have several advantages in that it is very straightforward and simple. It needs only the knowledge of the bathymetry plus an accurate measurement of the tension at the surface in order to assure proper tensioning at the bottom. In addition, there is no confusion due to currents and obscure cable angles at the surface.

It is concluded that the tension method by itself is not suitable for the deep water in the Alenuihaha Channel nor along steep slopes. In shallower, more protected waters with less steep bottom slopes, the tension method will be very suitable. Under these conditions, the static loads will be considerably smaller and the tensions due to bottom variation easier to measure. In addition, cable dynamics will be minimized in protected waters. Under all laying conditions, the tension is a valuable input to computing and confirming cable shapes and tensions below the vessel.

4.3.2 LENGTH METHOD

The length method of controlling bottom cable tension relies on accurate measurement of the total geometry of the cable laying situation such that a unique cable shape is determined and the bottom cable tension is computed. In order to keep track of the total geometry, the following must be known:

- Starting point of the cable
- History of the path of the cable laid on the bottom
- Length of cable deployed
- Position of the vessel
- Bathymetry along the cable path.
- Vessel Speed
- Current indicators

The length method does not have the disadvantages of trying to measure the top cable tension. Instead, it measures the length of cable deployed. Figure 3.2 illustrates the relationship between bottom tension and cable length deployed. For controlling bottom tensions within 2000kg, length of cable must be measured within 70m. This is a difficult task, if one considers the total cable length of 250km. There are a variety of methods for overcoming this problem:

- The cable is premeasured and marked by the cable manufacturer. Clearly identifiable marks are placed at 1km intervals, minimum, such that they can be detected during the cable lay and accumulated errors in cable length measurement corrected. The accuracies of these marks should be within ± 1m.

- Precise navigation of the surface vessel is required. Methods exist for 3 m accuracies (see Chapter 6).

- The cable path bathymetry must be known within 10 m over the entire cable route. The actual cable path versus the planned cable path must be accounted for during the cable laying.

- The cable starting point must be known with an accuracy of a few meters. This is easily accomplished within the commercial system because the cable starts from the shore. In the case of the HDWC Demonstration program, the starting point need not be as accurately determined, because the cable length is considerably shorter. For the HDWC program the starting point should be determined within 20m.

- There will be accumulated errors in the computed cable length along the bottom versus the actual cable length. These accumulated errors need to be periodically resolved. Chapter 5 discusses acoustic methods of locating positions on the bottom with an accuracy of 1% of the depth.

The length method of bottom tension control is not confused by bottom slopes along the cable path as is the case with the tension method. Both methods result in errors due to slopes which are perpendicular to the cable path.

There are significant errors introduced in the length method due to ocean currents aligned with the cable path. These have been illustrated in Figure 3.6. An inline current variation of 25% of the Alenuihaha baseline current imposes a variation of 70m in the proper cable length to maintain a 4000 kg bottom tension. As established before, the 70m is the maximum overall geometry tolerance, an undetected current variation this large would make the length method of solution unsuitable. It is also observed in figure 3.6 that the cable angle varies dramatically with current, the above current variation represents a 4.5^{o} top cable angle variation. Top cable angle is therefore a major indicator of current influence on the cable, the effect of bottom tension on cable angle is small (a 2000 kg bottom tension increase resulting in a length increase of 70m only increases the top cable angle by 0.8^{o}).

With the length method, a control signal must be given to the linear tensioning machine. This signal must be in the form of a tension command. The actual tension at the surface is computed in the same way as with the tension method: the tension at the bottom plus the weight of the cable times the depth of the touchdown point. The Integrated Control System computes this baseline tension and modifies it based on the difference between the actual and desired lengths of cable deployed. This modified signal forces the machine to correct the cable length. When the error between the desired and actual cable lengths approaches zero, the corrective signal diminishes.

The control tension signal to the CHSS can be looked at as an external amplified feedback signal (Figure 4.1). It has been shown earlier that geometrical changes to the cable shape below the vessel result in rather small tension variations at the CHSS. Under the tension method of controlling bottom tension, these small variations may not be sufficient to accurately drive the linear tensioning machine. The external integrated control system takes advantage of additional information from the navigational system and cable length measurements such that it can provide a corrective signal to the CHSS. As far as the CHSS is concerned, it behaves just as if there were a stronger tension response in the cable to variations in geometric shape. The size of the amplified feedback is a function of a programmable constant; this constant needs to be determined during the final design of the CHSS in order to optimize its response.

In conclusion, the length method works in some areas where the tension method is weak, notably down steep slopes and in deep rough water where tension measurements become unreliable. All geometrical measurements can be adequately measured; the major source of error is with currents.

4.3.3 ANGLE METHOD

There are variations in the surface cable angle as a result of bottom cable tension. Theoretically, by monitoring the surface cable angle one could control the bottom tension. As shown in Chapter 3, the cable angle variations are small for rather large variations in bottom cable tension, particularly at 7000 ft, and the cable angle is also a strong function of currents. While cable angle may not be suitable for measuring bottom tension directly, it does serve as a strong current indicator and can supplement both the length and tension methods.

4.3.4 COMBINATION OF METHODS

No one bottom cable tension method is best under all circumstances. Each has its advantages and disadvantages as outlined above. For this reason, it is advisable to compute the cable shape and bottom cable tension based on all available information. Figure 4.2 illustrates the block diagram for computing cable shape and the resulting tension command to the CHSS. Based on current top cable tension, cable length, vessel position, bathymetry, surface currents and top cable angles (the primary source of current influence), the touchdown point (and

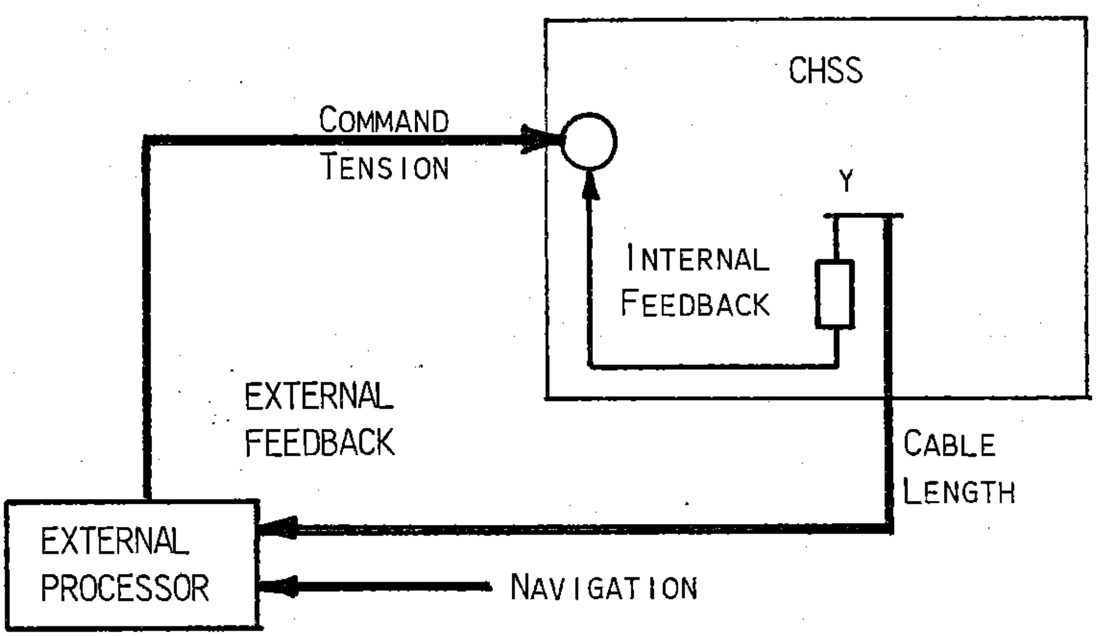


FIGURE 4.1 EXTERNAL "TENSION" FEEDBACK TO THE CHSS

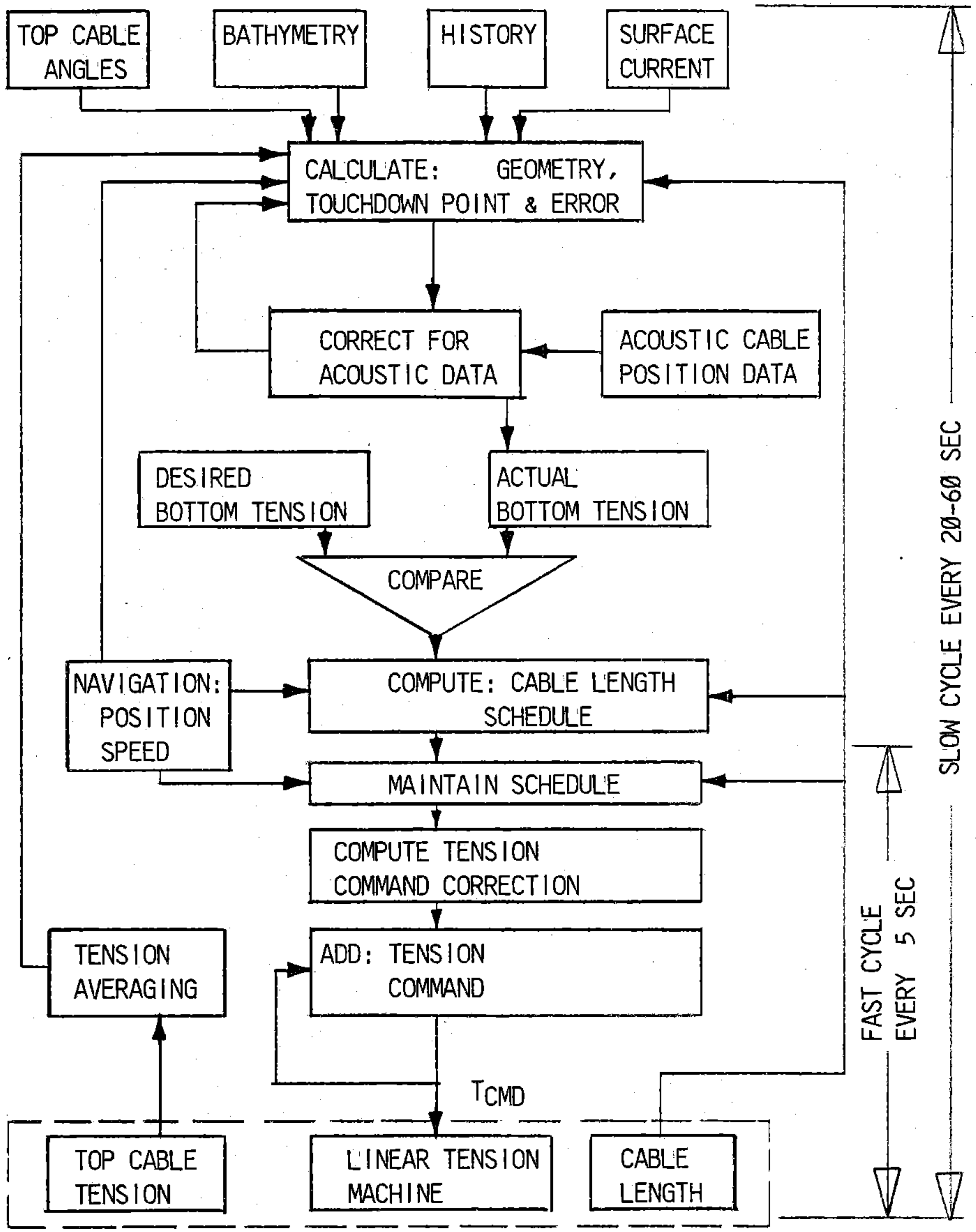


FIGURE 4.2 BLOCK DIAGRAM FOR BOTTOM CABLE TENSION CONTROL

error circle) is computed. The corresponding computed bottom tension is compared to the desired bottom tension and a corrective cable length determined. The corrective cable length is multiplied by a constant and added to the current tension command into the CHSS. In this way, a strong feedback signal is provided to the CHSS such that the payout velocity is appropriate for the bathymetry, vessel speed and bottom tension. Appropriate filters and corrective loops are necessary to insure smooth command signals to the CHSS

The input information in Figure 4.2 provides redundant information to the controller. Depending upon the laying circumstances (flat bottom, steep slopes, precision laying, high currents, etc.) one particular set of parameters will be established as the primary input--they will be the parameters which are most sensitive to improper laying. The "extra" parameters will be used to confirm proper operation and to help narrow the operating errors. In case of discrepancies, in input information, the human operator needs to be informed while the system continues to operate under its primary sensor inputs. The control software will be a fairly complex program.

4.4 AUTOMATIC VERSUS MANUAL CONTROL

The normal method of operating the linear tensioning machine is in a fully automated tension mode where it responds rapidly to variations in cable tension. There are options for manual control but the heave compensating capability of the machine could not be fully realized under manual control, a man simply does not have adequate response.

The command tension, however, can be either manually or automatically fed into the CHSS. Under a full automatic control a computer would calculate the appropriate tension command as outlined above, and digitally send this command to the CHSS. An alternative is having a man dial in the tension command which he could either read off a pre-printed chart and based on vessel position or taken directly from real time computer computations.

The man is generally more reliable than a machine except in the cases where he is not mentally or physically able to perform as well or in the case where it is a boring and tedious job from which he could become distracted. In this case, we have both situations. When operating under the tension method, the operator can simply dial in a tension based on vessel position only. This could be accomplished by simply reading off a pre-printed table. The job would be tedious, requiring constant watching of the navigational system and making slight corrections to the CHSS tension command. In the case of operating under the combination method of 4.3.4, the calculations are fairly sophisticated and would be extremely difficult to manually compute and impossible to compute prior to the cable laying. Under these conditions, a computer can do a far better job.

For controlling the CHSS, the controller computer should interface directly with the cable tensioning machinery. A full display of all parameters and computed range of errors should be available to a human operator dedicated solely to the CHSS. A rigorous schedule of manual checking and the possibility of manual override must be provided. In addition, sufficient information must be provided to the operator such that he can function alone, without the controller, in a contingency situation.

4.5 CONTINGENCIES

4.5.1 CONTROL SYSTEM FAILURES.

A variety of catastrophic failures can and probably will occur with the integrated control system. Such catastrophic failure would be a failure in the navigation system, loss of power or the controller computer goes down. The operator would immediately know that such a failure had occurred because of the loss of the control signal, the loss of the entire computer display or the computer signals that a critical input parameter is missing. Under such a situation, the operator and/or the controller would signal the system alarms. The CHSS tensioning machine would maintain the status quo. Once it detects that a command signal has been cut or that a system alarm has been initiated, it maintains the tension command preceding the alarm condition. The operator immediately reverts to manual control relying on printed tables which are provided continually by the controller when it is operating properly. These tables would include the latest information relative to currents, recent cable history, vessel speed, etc. For the commercial system cable laying, redundancy will be provided in all critical control equipment. The backup equipment can be brought on line and the CHSS put back under automatic control. For the HDWC demonstration program, less redundancy is required.

The more difficult contingency situation occurs when the problem is not so obvious. Problems such as program errors and sensor errors could become serious before the operator even knows there is a problem. The solution is in the early detection of such a problem. Redundant information is used to compute the bottom cable tension. Cable lengths, surface tensions and top cable angles should all agree within an acceptable error and these can furthermore be compared to values computed prior to the cable lay. The comparison between all systems can be done within the controller but the operator should have a rigorous schedule of checking the results to precomputed forms. In the case of a problem, the CHSS again maintains the status quo and the system reverts to manual control. The system remains on manual control until backup controllers can be brought online or the problem source detected.

4.5.2 CABLE HANDLING SUBSYSTEM FAILURES

There is a possibility that the cable tensioning machine or other components of the cable handling subsystem could undergo a catastrophic failure. Examples of such a failure would be loss of hydraulic pressure or the cable fouling on the deck (Western Gear). In this case, the linear tensioning machine would immediately stop paying out cable. Although this is not an intentional operation, the contingency must be provided for. The appropriate reaction would be for the controller and/or operator to sound an alarm and direct the vessel operator to stop forward motion as quickly as possible. The vessel would maintain itself along the cable path; backing down slightly on the cable maintaining an appropriate bottom cable tension. Under deep laying conditions, there is adequate time to stop the vessel. It may also be desirable to adjust the heading of the vessel to minimize heave on the cable since the CHSS is inoperable and no longer acting as a heave compensator. Once the CHSS is repaired, cable laying may continue.

The CHSS operator may also choose to bring the machinery to halt because of overheating, loose parts, etc. In this cause, the vessel is brought to a stop, and, with the controller operating properly, the cable payout will also come to a stop. At that point the CHSS is shut down and the same steps are taken as listed above.

CHAPTER 5

CABLE LOCATING INSTRUMENTATION

Knowing what happens to the cable once it passes through the overboarding sheave is important both for cable positioning and tensioning. This chapter reviews a variety of methods for monitoring cable location on the bottom.

5.1 CABLE LOCATING OBJECTIVES

A basic problem in the integrated control system is knowing where the cable is going after it leaves the vessel. For positioning the cable along a desired path, the surface vessel can be very accurately maintained along a desired position but currents may offset the cable once it leaves the vessel. Depending upon the accuracy required, this current deflection may need monitoring. In some cases, a very precise underwater location may be required to avoid underwater obstacles. Finally, the exact cable position should be documented either during or after the lay for future repairs and subsequent cable lays.

For cable tensioning, Chapter 4 points out several areas where knowledge of the cable location is required. Knowing the touchdown depth is necessary for proper cable tensioning and this can sometimes be difficult when laying along steep slopes. In addition, when laying by the length method there can be accumulated errors in the total length of the cable path along the bottom. A method is required whereby, at least periodically, a specific cable point is given a specific location on the bottom. In addition, it is desirable to provide underwater surveillance of the cable and bottom for contingency situations.

5.2 METHODS CONSIDERED

5.2.1 VEHICLES

One method of observing the cable on and near the bottom is to use a remote operating vehicle (ROV) or a manned submersible. There are a wide variety of submersibles that can operate at 600m (2000 ft) or less which is suitable for the majority of the commercial route. There are relatively few that can go to the bottom of the Alenuihaha Channel, two of these are the Navy's SEA CLIFF and the ALVIN from Woods Hole. These two submersibles occasionally come to Hawaii but would not be available for an extended program. There are major problems in dealing with submersibles on a cable laying operation. These submersibles, and particularly the large deep diving submersibles, are extremely limited in sea state for launch and recovery. They take a considerable length of time to reach the bottom and their speed, endurance and distance is greatly limited. A typical submersible dive may take four or five hours and cover one or two miles along the ocean bottom. Longer endurance is not possible due to the power and life support limitations.

Remote operated vehicles, on the other hand, are tethered and unmanned. They are not life support limited and power supplied from the surface. They can be generally configured with a wide variety of underwater instrumentation including cameras, video, and acoustic navigational equipment. Most ROVs are outfitted with manipulators and can do limited work on the bottom.

There is currently only one ROV capable of the depths in the Alenuihaha Channel. This is the HYDRA 2500 which has a depth capability of 2500m (8200 ft) and is operated by Oceaneering International, Inc. At present, there is only one of these systems available and it has been on lease within the oil industry for the last few years. Oceaneering has plans for building several others as the deep diving needs expands. Costs for the HYDRA 2500 is $7750/day plus $1600/day for the crew operating on a 12 hour basis. For 24 hour operation, the total cost for equipment and crew would be $10,150/day.

There are operational limitations in working with an ROV in 2000m of water. The maximum speed on the bottom would be limited to .25m/s (1/2knot) because the vehicle must drag along an umbilical. The .25m/s (1/2 knot) speed limitation is also the upper practical limit for following a cable with video. At faster speeds, the operator cannot properly respond or view. The vehicle operates out of a cage on the bottom. The cage is heavy and holds down the main umbilical while the ROV is free to move about on a lighter umbilical without the cage. Moving along the cable would require the cage being towed from the surface vessel. This "live boating" is not their normal mode of operation but can be done. In areas of steep slopes and large boulders, additional acoustic equipment would be necessary on a vehicle to help maintain it a fixed distance off the bottom. To reach 2000m depth would take approximately 1 1/2 hours down and 1 1/2 hours back up. The maximum time on the bottom would be 48 hours if there are not problems; there must be periodic maintenance periods. Relative to continuous operation, the project would require two complete operating systems, two vehicles and two operating crews to be able to get full time, 24 hours/day, coverage. (Two such systems do not presently exist). To go to sea today with Oceaneering's present system of one winch and umbilical plus two vehicles, 30% down time should allowed in the operational plan.

5.2.2 ACOUSTIC SENSORS

Acoustic methods are the most widely used techniques for measuring distances under water and there are a wide variety of commercial systems available. All the methods proposed involve placing of acoustic transmitter on the cable.

The simplest method would be to place a depth transmitting pinger on the cable. As the pinger goes down with the cable, it transmit the depth in either a coded signal or as a frequency change. Accuracies of 1% of depth are routinely achievable. A surface vessel behind the cable vessel could monitor the pinger's signal and determine the touchdown depth. The transponders can be attached by clamping a pendant wire rope to the main cable while slowing or stopping the cable laying operation. The buoyant transponders can be retrieved by an acoustic release and picked up by the surface vessel or collected by an ROV doing inspection and/or guidance of the cable.

The next order of sophistication and accuracy with acoustic systems would be a surface oriented acoustic position indicator. These systems consists simply of a vessel mounted transponder which is aligned to the vessel fore and aft line or gyro stabilized. The surface transducer ranges to a transponder underwater and from the resulting slant range, azimuth and depth, a position on the underwater transponder can be derived. The system is affected by water column conditions and any pitch or roll at the surface unit is immediately translated into a position error at the underwater transducer. Partial compensation for these problems are possible and accuracies are in the order of 1% of depth translated into horizontal error. Examples of surface acoustic position indicators are: Honeywell 900 series, EDO Western Hydro Star, ORE Navtrac. The great advantage of this system is that it is flexible and can be moved rapidly where it is required.

An even more accurate acoustic positioning system is possible by placing a number of seabed transponders at selected points on the ocean floor. With a large number of transponders on the bottom and a surface transponder as discussed in the previous paragraph, all possible baselines can be measured accurately locking in the entire seabed grid. Once the absolute calibration of the seabed grid is performed, the surface positioning system is no longer required. Any additional transponder moving about the grid on either an ROV or when attached to the cable, can be very accurately positioned relative to the seabed transponders. Accuracies from such a system are ± 3m horizontally and depth accuracy to 0.1%. The main disadvantage of such a system is that it requires a great number of seabed transponders which, in the case of the cable lay, would be required along the long corridor. The maximum range of a transponder is in the order of 7km; for a corridor-type positioning task, one transponder per 2km of corridor is a reasonable estimate. Typical of such systems are Oceano, Geodata Marec and Sonardyne.

A general comparison between the seabed and the surface acoustic systems are provided below:

	Seabed	Surface
Calibration required?	yes	no
Spaciously Flexible?	no	yes
Affected by Water Column Charateristics?	some	very
Affected by Surface Conditions?	no	very
Accuracy?	±3m	±1% depth
Expensive?	yes	less

The primary difference between cost for the two systems is not in equipment but in transponder placement, calibration and retrieval for the subsea system.

5.2.3 CABLE ANGLE SENSORS

The surface cable angle is valuable both for serving as an indicator of current deflection, as backup information on bottom cable tension and for insuring that the cable heading is appropriate to avoid improper cable deflection at the sheave (see Figure 3-1).

There are a variety of methods of measuring cable angles. Some obvious visual angles can be taken relative to the vessel by painting indicator lines on the sheave fixed fairlead. This would give the angle alpha shown in Figure 3-1 and would be observed by standing well to one side of the overboarding sheave. A second observer standing directly over the sheave could develop a "feel" for the angle, beta, which is the deflection the cable makes relative to the plane of the sheave. Relying on human observers, however, takes up the time of two people in a rather dull job and leaves room for interpretation because of the motions of the vessel and cable.

Alternative, electronic means of measuring cable angle are possible. Figure 5-1 illustrates three possible methods. The method shown in Sketch A measures the cable angle relative to the vessel. A pair of idler pulleys rides the cable after it leaves the overboarding sheave. A flexible arm attaches these idler pulleys to the vessel and angular measurements are made electronically at the base of this arm. This system would give accurate cable measurement relative to the vessel and could be either compared to vessel roll and pitch data to obtain an instantaneous cable angle or it could be averaged over a period of time, assuming the vessel is level on the average, to obtain absolute cable angles.

Figure 5.1(B) illustrates an acoustic method of measuring cable angle. Two transponders below the vessel could interrogate a third transponder riding the cable a fixed distance below the overboarding sheave. From these two distances, cable angles could be determined. Again, cable angles are relative to

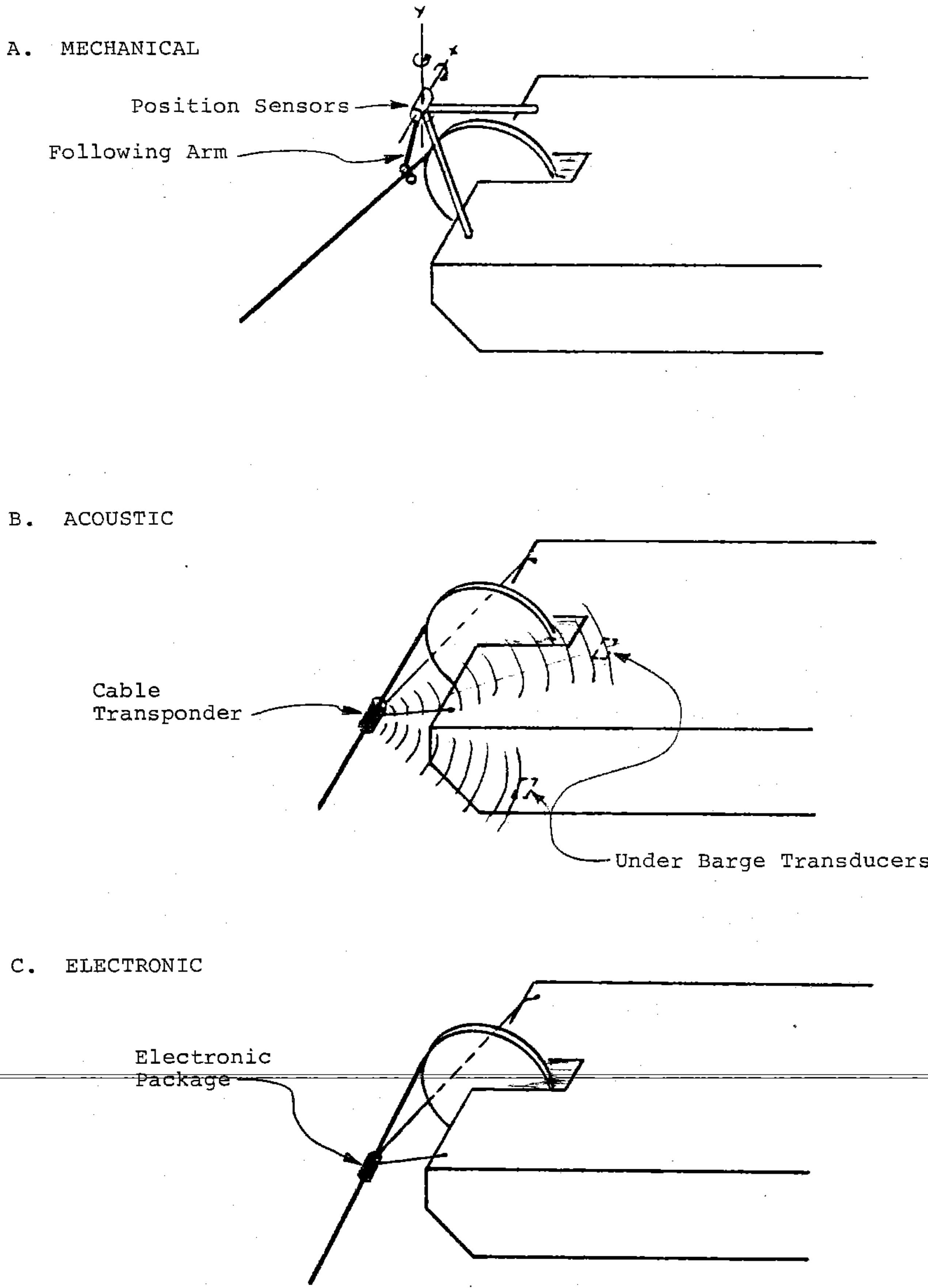


FIGURE 5.1 METHODS OF MEASURING SURFACE CABLE ANGLES

the vessel but could be compared to vessel motion data to obtain instantaneous cable angle values or averaged over time to get the same values.

Option C shown in Figure 5.1 illustrates an electronic package suspended form the cable below the overboarding sheave. Internal to the package would be a gravity sensor and a compass such that the absolute cable angle could be read and transmitted to the vessel at any given time. As far as we know, such an electronic package does not exist.

All three systems proposed require some form of mechanically attaching to the cable at some point after the overboarding sheave. This will cause a problem with the attachment of bottom locating transducers onto the cable; they must pass through the angle detection system. All of them could be configured such that they could accommodate this transducer but this would be an important design constraint. In any case, none of the cable angle locating devices proposed exist, to our knowledge, and would have to be developed. The technology is not difficult; it is simply not an off-the-shelf item.

5.2.4 CURRENT MEASUREMENTS

Currents represent the major uncertainty relative to cable placement and bottom tensioning. Currents can be measured directly with current profilers dropped from the cable laying vessel, from an alternative vessel or from a statically moored array. These measurements, however, are not easily integrated into a control system. The easiest indicator of currents would be to measure water velocity and water direction relative to the cable laying vessel. The vessel's actual velocity is precisely known and therefore the surface current could be computed. Such an instrument would be hung below the vessel at a point which minimizes heave due to roll and pitch and the information taken directly into the controller. Major surface currents could then be monitored and used as an indication as to whether there are shifts in current status necessitating another acoustic positioning measurement.

5.3 RECOMMENDED METHODS

5.3.1 CABLE POSITIONING

For indicating cable offset during the cable lay, several methods are recommended. It is recommended the cable angle at the surface be monitored as a rough indicator of cable position to the right or left of the vessel path. This cable angle needs to be monitored in any case for purposes of proper ship heading due to overboarding sheave restrictions. The cable angle information should therefore also be used as an indicator of overall cable offset. Reference should be made to Chapter 3 on the importance of cable angle to cable statics. In many cases, simple knowledge of the cable angle may be satisfactory for cable placement accuracy on the bottom.

In some cases, higher accuracy may be required. A surface oriented acoustic system can be used by tying transponders onto the cable at intervals determined by the ship's operator. Depending upon his uncertainty and the cable placement accuracy required, more or less transponders can be used. The transponders would be positioned by a separate ship following the cable laying vessel. Placement information from each transponder could be radioed to the vessel and manually entered into the controller. During the commercial operation, the transponder should be recovered with a ROV. During the HDWC demonstration program, the transducers will be recovered with the cable. It is not anticipated that a seabed acoustic system will be required to determine cable offset.

A surface current measuring system relative to the laying vessel is recommended for determining an estimate of the major cable offsetting force and to serve as an indicator of current variations. This data is also valuable to the positioning system.

For the precise location of the cable on the bottom, the cable laying operation is drastically altered. The use of a remote operated vehicle is recommended for following directly behind the cable and watching the touchdown point. To avoid using a seabed acoustic system, a visual reference is recommended such as prelaying a wire rope along the desired path. This is a similar operation to that done by Pirelli in their cable lay to Sicily. The ROV would give direct visual feedback to the cable vessel. To do this operation in 2000m of water is well beyond the current cable laying state-of-the-art. It is not known whether this requirement exists for the Hawaiian commercial program and, until that is determined, it has not been pursued in detail in this study.

5.3.2 CABLE TENSIONING

For cable tensioning control, the touchdown depth needs to be known, particularly along slopes. In addition, an occasional precise location on the bottom for a given point on the cable is necessary in order to avoid accumulated errors when operating under the length method of bottom cable tensioning. This information can be achieved periodically with transponders on the cable monitored with a surface acoustic positioning system.

If, in the commercial system, the cable is laid south of Maui along the 1900m contour, a bend in the cable route must be negotiated in the middle of the Alenuihaha Channel. This bend would introduce significant length uncertainties as to the cable position on the bottom. Because of the great depth, the best horizontal accuracy for a point on the bottom achieved with a surface oriented positioning system would be 20m. This corresponds to a tension error of 500kg in Figure 3.2, certainly an acceptable tolerance.

For the HDWC demonstration program, the surface acoustic positioning system can also be used to supplement the length method of the bottom cable tensioning. The main problem in the HDWC program is establishing the starting point of the cable lay. For a cable lay that commences in 2000m, the starting point accuracy is ± 20m. with the same acceptable tolerances as above.

5.3.3 ANCILLARY EQUIPMENT

With any acoustic system, the characteristics of the water column on site need to be known. Due to the depths involved, an expendable system is recommended such as the SIPPICAN XBT temperature, depth and salinity probe. This is necessary to accurately determine the acoustic velocity in seawater.

Data handling for the acoustic systems is normally conducted with a microcomputer coupled to a plotter. This data needs to be transmitted into the controller thereby requiring additional interfacing work.

SECTION 6

NAVIGATION

In previous chapters of this report it has been shown that a continuous, accurate indication of cable laying vessel position is very important to the cable laying control system. Knowledge of vessel position along the presurveyed cable path yields information about the current bottom conditions, depth, slope, type of terrain, that is essential to guide cable payout and vessel speed. A record of the exact vessel path and the associated bathymetry along that path, allows accurate calculation of the total cable length laid, which is required to determine cable bottom tension. A navigation system is needed that will supply vessel position with speed, accuracy and reliability. The purpose of this chapter is to survey navigation techniques and devices which might be applicable for use in both the commercial cable laying and HDWC programs. From the survey and a list of basic system requirements, a ranking system is developed for the navigation systems. Finally, a navigation system based on commercially available equipment is recommeded.

6.1 POSITIONING SYSTEMS STUDIED

Six different positioning systems were included in this study. These are the most commonly used precision navigation systems:

- OMEGA
- LORAN C
- Satellite: Transit and Global Positioning System
- Microwave Radio Positioning
- High Frequency Radio Positioning
- Very High Frequency Radio Positioning

The method of operation, accuracy, error sources, sampling frequency and commercial availability of each of these systems will be briefly reviewed.

6.1.1. OMEGA

A. Method of Operation

OMEGA is a world wide navigation system that utilizes very-low-frequency (VLF), 9 to 14 KHz, electromagnetic signals for hyperbolic position fixing by phase comparison techniques. There are eight OMEGA broadcast stations around the world which transmit VLF signals using the "D" layer of the ionosphere and the earth's surface as a wave guide.

B. Accuracy

The system is designed to have an accuracy of 5.6 km (3.5 mi)which can be improved to an accuracy of up to 90m (295 ft.) with the use of differential positioning. Differential positioning is a technique where a receiver is placed at a known location and the difference between the fix provided by the receiver and its known location is broadcast as a correction factor to other receivers in the vicinity.

C. Error Sources

Predictable sources of error include day/night transition, magnetic bearing, ground conductivity and auroral zones. Such predictable errors can be corrected using readily available correction charts. Unpredictable sources of error include sudden ionospheric disturbances and polar cap anomalies which can cause errors of up to 14.8 km (9.21 mi) in the basic system.

D. Sampling Frequency

A fix is provided once every 8 seconds at the completion of the OMEGA broadcast cycle.

E. Commercially Available Systems

A variety of commercial OMEGA receivers are available. Prices vary with equipment sophistication: Differential positioning systems are much more expensive. A listing of various OMEGA receiver systems is provided below:

- Sercel M6, automatic differential OMEGA, approx. $110,000
- Magnavox SRN-12,

6.1.2. LORAN C

A. Method of Operation

LORAN C is a limited coverage navigation system using low-frequency, 90 to 100 kHz, signals for hyperbolic position fixing. The time difference between reception of pulsed and coded signals from one master and two secondary transmitting stations is used to plot position on LORAN C navigation charts. There are 13 LORAN C coverage areas around the world. The main Hawaiian Islands are not in a coverage area.

B. Accuracy

The systems are design to have an accuracy of 185-463 m (607-1520 ft). This can be improved to 1 m.(3.28 ft.) with differential positioning.

C. Error Sources

Sky wave interference is the most common error source in LORAN C use. The ground wave is relatively free from atmospheric interference.

D. Sampling Frequency

Approximately 3 minutes is required for an initial fix with 1 minute required for each fix thereafter.

E. Commercially Available Systems

Commercial LORAN C receivers are available with a wide range of options and prices. As with OMEGA receivers, differential positioning systems are much more expensive. A listing of various LORAN C receivers is provided below:

- Internav LC-300, basic receiver/navigation system, displays time differences or Lat/Lon, Time/Distance, Range/Bearing. Approx. - $1900
- Internav LC-408, precision receiver for surveying, positioning and monitoring. Approx. - $14,200

6.1.3. SATELLITE: TRANSIT AND GLOBAL POSITIONING SYSTEM

There are two satellite navigation systems currently in operation: The Transit system and the Global Positioning System (GPS). The Transit system was developed by the Navy in the early 1960s for navigation and positioning of Navy ships and submarines. For some years the Navy has allowed civilian users to take advantage of the system. The end of Transit's planned service life is scheduled for between 1993 to 2000. Transit's successor is the Navstar GPS. The GPS has been under development for 10 years and will eventually include an 18 satellite network. Five Navstar satellites are currently operational.

A. Transit

1. Method of operation. There are 5 Transit satellites orbiting the earth in polar orbit with periods of 1 hour 47 minutes. The satellites broadcast a serial stream of digital data which contains a navigational message defining the position of the satellite with respect to time. A receiver monitors the Doppler effect caused by the moving satellite and turning of the earth. The Doppler frequency data and the information defining the position of the satellite in time are combined to determine the location of the receiver. The Transit system offers worldwide coverage.

2. Accuracy. Accuracies of up to 5 m (16.4 ft.) have been achieved using multiple Transit satellite passes. Accuracies of 20 m (65.6 ft.) are possible with one satellite pass and differential positioning can be used to increase accuracy up to 1 m (3.28 ft.)

3. Error Sources. As the Transit satellites near the end of their planned service lives the data quality emitted from them is deteriorating. Weak signals from satellites as well as receiver equipment failure are the primary sources of error. The system is not affected by atmospheric disturbances.

4. Sampling Frequency. A satellite will pass within the line of site of any receiving antenna on an average of every 1.5 to 2 hours. This means that occasionally satellites will pass by much more frequently, and likewise periods of 6 hours will sometimes pass without a satellite coming in view. Satellite coverage is poorest near the equator and best near the poles.

5. Commercially Available Systems. Magnovox was the first to produce commercial transit receivers, borrowing from technology they had developed for military transit operations. Transit receivers are available from several manufacturers: A sample listing is provided below:

- Magnavox MX 1502 Satellite Surveyor, approx. - $48,000
- JMR Global Surveyor, approx. - $62,500

B. Global Positioning System

1. Method of Operation. GPS is a worldwide three dimensional positioning system. The position determination is based on measurements of the time of arrival (TOA) of a coded train of pulses emitted simultaneously from four satellites whose positions are defined by the satellite orbit message. Each set of four TOA measurements provides data for the determination of clock time offset, latitude, longitude and altitude.

2. Accuracy. Two levels of accuracy are built into the GPS. The Standard Positioning Service available to all users yields spherical error probability of 15-47 m.(49-154 ft.) with the possibility of improvement to 3-5 m.(9.8-16.4 ft.) using differential positioning. The highest level of accuracy is obtained from the Precise Positioning Service. Current policy limits use of this service to users who can demonstrate that their use is of vital national interest.

3. Error Sources. Error sources are unknown. The system is designed for all weather operation and as such is most likely minimally affected by atmospheric disturbances.

4. Sampling Frequency. At this time only 5 of 18 satellites are in orbit and coverage is limited to 4 to 10 hours per day. During the coverage period 20 minutes is required to obtain the initial fix and updates are provided every 1.5 seconds thereafter.

5. Commercially Available Systems. The following is a partial listing of currently marketed Navstar receivers:

- TI Navstar Navigator, approx. - $139,800

6.1.4 MICROWAVE RADIO POSITIONING

A. Method of Operation

Microwave positioning systems use radio line of sight, range-range positioning, which compares the distance from one or more offshore interrogator units to 2, 3 or 4 shore based responding units. The three main methods of obtaining the distance between interrogator and responding units are:

- Phase comparison of continuous waves
- Phase comparison of microwave modulation
- Time counting between pulsed signals

The output from these systems varies from digital display of the range distances to X-Y position and course correction information.

B. Accuracy

X-Y position accuracy is a function of both range accuracy and interrogator location with respect to the responding units. In a 2 responder system, with the angle formed by the 2 responder-interrogator lines of sight between 30^{o} and 150^{o}, accuracies of 2.2-7.7 m (7.2-25.3 ft) are achieved. With the use of 3 or 4 responding units positioned at angles sharper that 30^{o} or wider than 150^{o}, greater accuracy can be achieved.

C. Range

Microwave systems are available with maximum ranges between 30 and 175 km (18.6-109 mi). The operational range of a given system is dependent on antenna height and the corresponding radio line of sight.

D. Error Sources

There are two potential error sources to which microwave positioning systems are susceptible: These are atmospheric interference and signal reflection.

1. Atmospheric Interference. Rainfall, fog, sandstorms or hail occurring anywhere between the interrogator and responder units will attenuate the signal and reduce the system range.

2. Signal Reflection. Phase cancellation occurs when two waves, 180° out of phase but with equal amplitude arrive almost simultaneously at the interrogator. This condition is generally due to a direct wave and a reflected wave (reflected off the water's surface) arriving at the interrogator's receiver simultaneously. Phase cancellation is dependent on the geometry established by the interrogator and responder heights relative to the water surface and the distance between them. Use of two interrogator units mounted at different heights on the vessel mast can overcome this error. Wave reflection off ships, airplanes and fences can also create erroneous position readings.

E. Sampling Frequency

All systems establish a single fix approximately once every 50 msec. The user can specify the number of fixes to be used in position processing to produce a fix of required accuracy.

F. Commercially Available Systems

The following is a partial listing of commercial microwave positioning systems:

- Falcon Miniranger 484, Motorola, 74 km (46 mi) range, approx. - $50,000
- Trisponder 540, Del Norte Technology, 80 km (50 mi) range, approx. - $50,000
- Autotape DM 43, Cubic Western Data, 150 km (93.2 mi) range, approx. - $125,000
- MRD 1, Tellurometer Limited, 100 km (62.1 mi) range, approx. - $90,000
- Micro-fix, Racal Positioning Systems, 80 km (50 mi) range, approx. - $50,000

6.1.5. HIGH FREQUENCY RADIO POSITIONING

A. Method of Operation

High frequency (HF) radio positioning systems are long range systems that utilize over the radio horizon range-range and/or hyperbolic techniques to determine position. HF waves are reflected by the "E" layer of the ionosphere which makes over the horizon positioning possible. A system consists of fixed position, shore based responders (at least two) and a portable interrogator. Distances are obtained with either phase comparison, pulse counting or a combination of these techniques.

B. Accuracy

Range accuracies of 1-5 m (3.28-16.4 ft) are claimed by all systems with positional accuracies dependent on positioning method used, antenna location and overall range.

C. Range

Range varies from 450-750 km (280-466 mi)

D. Error Sources

The HF positioning equipment is dependent on a wave guide formed by the E-layer of the ionoshpere and the earth's surface. Reflection of the E-layer is best during daytime and poorer during the night when HF range is reduced by as much as 50%. Greatest interference occurs during sunrise and sunset. Other sources of error, which affect all radio positioning systems to varying degrees, are conductivity variation in seawater, sudden ionospheric disturbances and signal cancellations due to reflected waves off the water surface.

E. Sampling Frequency

The positional fix frequency varies from approximately 10 fixes per second to substantially higher rates.

F. Commercially Available Systems

A partial listing of commercial HF systems is provided below:

- Argo DM 54, Cubic Western Data, approx. - $180,000
- Hi-Fix/6, Racal Decca, approx. - $80,000
- Lorac, LORAC Service Corporation, approx. - $185,000
- Raydist DRS-H, Teledyne Hastings-Raydist, approx. - $100,000

6.1.6. VERY HIGH FREQUENCY RADIO POSITIONING

A. Method of Operation

The Very High Frequency (VHF) radio positioning systems employ the same operational methods as HF systems. However, they operate in two distinct modes: line-of-sight and non-line-of-sight. In non-line-of-sight operation signal propagation is accomplished by tropospheric scatter.

B. Accuracy

Accuracy of VHF systems varies dependent on if they are working within line-of-sight of the interrogator. During line-of-sight operations accuracy is 2-3 m (6.56-9.84 ft). Accuracies beyond 75 km (46.6 mi), non-line-of-sight, varies due to uncertainties caused by tropospheric scattering in the upper atmosphere.

C. Range

VHF systems have maximum ranges varing from 100-350 km (62.1-217 mi) depending on antenna configuration and power.

D. Error Sources

VHF systems are subject to the same general error sources that affect all radio positioning systems. Reception of reflected waves is a principal concern and antirefractive devices such as dual antenna systems are used to correct this error.

E. Sampling Frequency

Positional fixes are available at a frequency of approximately 10 per second, and the user is generally able to specify the display frequency desired.

F. Commercially Available Systems

A partial listing of commercial VHF systems is provided below:

- Syledis, Sercel, approx. - $80,000
- Maxiran, Maxiran Corporation, approx. - $120.000
- XR Shoran, Offshore Navigation, no price avail.
- 545 Trisponder, Del Norte Technology, no price avail.

6.2 REQUIREMENTS OF THE POSITIONING SYSTEM

6.2.1. ACCURACY

As discussed in Chapter 3 the required accuracy for the vessel positioning system is different along the cable path from perpendicular to the path. However, the positioning systems just reviewed generally describe their accuracy in terms of an error circle radius, and the accuracy of all radio positioning systems is largely a function of vessel heading, position relative to the fixed shore based responder units and number of responders interrogated. Therefore, for the purposes of this study, required accuracy will be defined in terms of an error circle radius. For the evaluation which follows it is assumed that an error circle radius of 10 m (32.8 ft) will be a minimum requirement of the navigation system during the commercial and HDWC cable laying operations. An even more accurate system with an error circle radius of 3 m (9.84 ft) may be required in certain locations such as when traversing particularly rough terrain or laying parallel to bathymetric contours. Final specification of navigation system accuracy will be dependent on the results received from more accurate cable path surveys.

6.2.2. RANGE

Range is important only relative to radio wave positioning systems. The greatest potential distance between vessel receivers and fixed responders is from Ule Point on Kahoolawe to a point 13 km (8.1 mi) off of Upolu Point on Hawaii, a distance of 68.2 km (42.4 mi). A system with this minimum range during less than perfect atmospheric conditions will be required. This range requirement is reduced somewhat in the HDWC program where the greatest distance likely to be encountered is 65.0 km (40.4 mi).

6.2.3. SAMPLING FREQUENCY

The positioning system must provide navigational fixes at a rate that will allow the propulsion system and cable handling subsystem to maintain cable/vessel position and cable tension within acceptable tolerance ranges. A value of one fix per second is considered a minimum requirement for both the commercial and HDWC program.

6.2.4. RELIABILITY

Cable laying vessel position has been identified as a critical item relative to the objectives of the overall control system. Failure of the navigation system would be catastrophic. Therefore, the navigation system must be able to overcome identified error sources and be supplied with adequate redundancy to meet potential equipment failures. A system with a record for low equipment failure based on user evaluation will be most desirable for both the commercial and HDWC programs.

6.2.5. COMPUTER INTERFACE

The navigation system must be able to communicate digitally with the positioning controller if the system is to be fully automated as proposed in Chapter 4. Standard computer interfaces such as IEEE 488 or RS232C will be required for both the commercial and HDWC programs.

6.3 POSITIONING SYSTEM EVALUATION

A summary of the navigation system requirements for the commercial cable laying operation is presented below:

- Accuracy -- <10 m (32.8 ft) error circle radius.
- Range -- 85 km (52.8 mi) under less than perfect atmospheric conditions.
- Sampling Frequency -- 1 navigational fix per second.
- Reliability -- System with lowest equipment failure rate possible.
- Computer Interface -- IEEE488, RS232C or comparable.

In the following table, Table 6-1, the six positioning techniques are evaluated as being acceptable or unacceptable in terms of accuracy, range, sampling frequency and computer interface requirements. The techniques which satisfy all four criteria are then further evaluated in terms of cost and reliability.

TABLE 6-1

Positioning Technique	Accuracy	Range	Sampling Frequency	Computer Interface
OMEGA	U	A	A	A
LORAN C	U	A	A	A
SATELLITE	A	A	U	A
MICROWAVE	A	A	A	A
HF	A	A	A	A
VHF	A	A	A	A

A = Acceptable U = Unacceptable

The microwave, HF and VHF radio navigation systems are all able to satisfy the requirements tabulated above. Further considerations are system cost and reliability.

6.3.1. COST

The price ranges of the three radio positioning systems are listed below.

- Microwave Positioning $50,000-$125,000
- High Frequency Positioning $80,000-$180,000
- Very High Frequency Positioning $80,000-$120,000

Obviously, if everything else is treated as equal, a microwave system could provide the greatest accuracy for the least cost.

6.3.2. RELIABILITY

An extensive survey of past users of microwave, HF or VHF navigation systems was not undertaken as part of this study.

However, if HF and VHF systems are excluded on the basis of cost, there are a number of local users of microwave systems who were able to give indications of problems they had experienced. Some of the reported failures were potentially caused by human error, and all failures reported could have been overcome by backup or redundant units.

6.4 NAVIGATION SYSTEM RECOMMENDATIONS

A microwave radio navigation system appears to offer the best accuracy at the lowest cost of all the systems surveyed. Microwave radio navigation systems are able to give reliable performance under a variety of atmospheric conditions and throughout the day and night. The particular microwave system recommended is the Motorola Miniranger Falcon IV Navigator. This recommendation is based on the Miniranger's position as one of the first microwave positioning systems on the market. Hence, its accuracy and reliability are well documented, and its price is among the lowest on the market. Figure 6-1 is a map of cable route option 1 that includes the required positions for the Motorola Universal Reference Stations in order to provide adequate navigational coverage along the route. It is envisioned that Reference Stations would be moved as the lay vessel progressed along the cable path to minimize the overall cost of the system. The following is a summary of the important specifications of the Falcon IV system. More complete manufacturer documentation on this system is provided as an appendix to this chapter.

MOTOROLA MINIRANGER FALCON IV

Accuracy: Approaches $\pm$2 m ($\pm$6.56 ft) when 4 responders are in use; 2.8-7.7 m (9.2-25.2 ft) when only 2 responder stations are in use.

Internal Processing: When only two shore based responder stations are being interrogated, the miniranger solves for X-Y position by simple trilateration. If greater than 2 responder stations are under interrogation, A least squares algorithm and a second order predictive filter (based on constant velocity and user supplied tolerance) is used.

Sampling Frequency: 1 second in X-Y mode.

Physical dimensions: Range Processor - 14x46x43 cm (5.5x18.1x16.9 in)
Control Display Unit - 16x28x28 cm (6.3x11x11 in)
Receiver/Transmitter - 31x21x17 cm (12x8.3x6.7 in)

REQUIRED POSITIONS FOR
MICROWAVE RADIO POSITIONING
SYSTEM RESPONDER UNITS

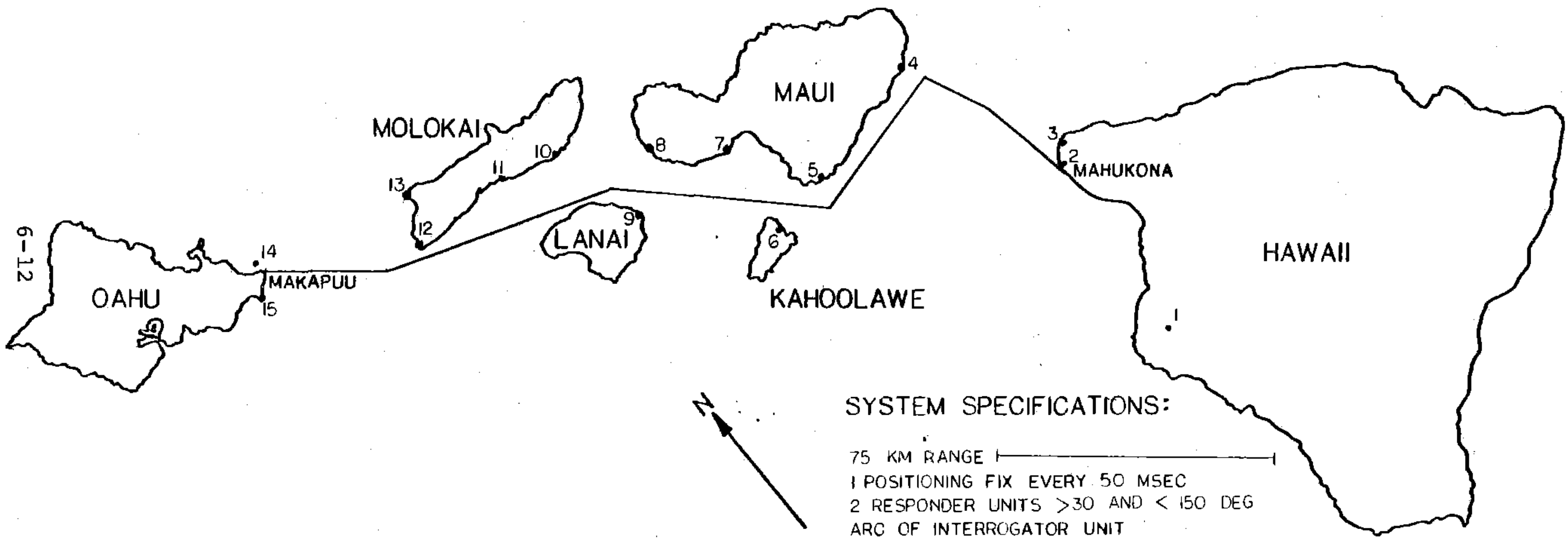


FIGURE 6.1

Cost: Range Processor + Control Display Unit + 2 Universal Reference Stations + 1 Receiver/Transmitter = $43,100.
Additional Universal Reference Stations = $7892
Additional Receiver/Transmitters = $7892

Availability: Purchase or lease @ 15% of purchase price per month.

Redundancy: Complete backup or redundant system suggested consisting of 2 receiver/transmitters and processor/control unit. A total of 12 Universal Reference Stations should be purchased for convenient coverage and adequate redundancy.

SECTION 7

VESSEL PROPULSION

The objectives of this study were twofold. First, we modeled the environmental and task-related loading on a cable vessel to establish the vessel propulsion and positioning requirements as a function of environmental conditions. The complete time-dependent (dynamic) version of such a mathematical model was postulated. However, to obtain the information necessary for conceptual design of an integrated vessel control system, the complete model was reduced to an equilibrium or time-independent (static) model. That is, only the static components of environmental and task-related loads on the vessel were estimated to size the propulsion and positioning requirements. Second, we surveyed operators and manufacturers to identify generic propulsion/positioning systems and system components (e.g., thrusters, tugs) and to postulate and evaluate propulsion/positioning configurations with the equilibrium model.

A summary of similar operations and a review of Tugs and Propulsion/Positioning Systems available is given in Section 7.1. Potential configurations are presented in Section 7.2. The Baseline Barge with Tugs providing propulsion and positioning is considered as well as the Barge with Fixed (Non-Steerable) or Rotatable (Steerable) Thrusters providing propulsion and positioning. In Section 7.3 the equilibrium(time-independent)model is presented, and power and positioning requirements are established for the generic configurations. The equilibrium model considers the steady component of wind and wave-drift forces and yaw moments and the drag force and moment due to the relative velocity between the water and vessel. The task-related loads due to the horizontal projections of the steady component of top cable tension are also considered. The cable touchdown point and, therefore, cable equilibrium path is also obtained.

Given the information presently available throughout this section and for the purpose of sizing propulsion/positioning components, the baseline barge as summarized in Table 7.1 is considered operating at arbitrary headings under the Alenuihaha environment. An extreme operational environment is assumed corresponding to colinear winds, current and seas of magnitude corresponding to the Alenuihaha conditions. Only scenarios resulting in cable/barge angles within the values required by the relationship given in Table 7.1 are considered for sizing the propulsion/positioning system.

The barge is considered deploying a cable with properties corresponding to the nominal values from the previous study of cable dynamics (Reference 7.1). The Pirelli Cable No 116 was not selected on time for incorporation into this study.

Fortunately, the nominal values from Reference 7.1 for overall cable diameter and wet weight are larger than values corresponding to No 116 such that at the conceptual design phase it is not necessary to update estimates of task-related loads given in Section 7.3 (i.e., 133 mm diameter and 32.1 kg/m as compared to 119.5 mm and 25.8 kg/m).

Conclusions and Recommendations are summarized in Section 7.4. Relevant information gathered during the survey of propulsion/positioning systems is documented in the appendices.

Table 7.1

BASELINE BARGE, ENVIRONMENT AND OPERATIONAL RESTRICTIONS

Baseline Barge

LOA	122m (400 ft)
LBP	116m (380 ft)
Beam	30.5m (100 ft)
Draught (Operational)	3m (10 ft)
Height	6.1m (20 ft)
C_B	0.88
Displacement	9803 t (9650 LT)
- Lightship	3708 t (3650 LT)
- Deadweight	6095 t (6000 LT)

(Note: Normally, 100 km of 40 kg/m cable will be loaded in a turntable such that there is at least 2,000 t available for deck and cable handling equipment as well as ballast.)

Baseline Environment [V_c , Speed along route, : 1m/sec (2knts)]

- Alenuihaha Channel

  Wind: 18 m/s (35 knots) from 60° T

  Surface Current: 1.5 m/s (3 knots) toward 50° T

  Waves:

  Seas: 2.4m (8 ft) Significant Height
  6.1 secs. Significant Period from 70°T

  Swell: 1.2m (4 ft) Significant Height
  13 secs. Significant Period from 190° T

  Maximum Water Depth: 2134m (7000 ft)

- Extreme Operational

  Colinear Wind, Current and Seas of Alenuihaha Magnitude

Operational Restrictions

Cable Handling System such that:

$$\sin \alpha_H \cos \alpha_V < 0.174$$

where,

α_H (α_V): the horizontal (vertical) cable/barge angle.

7.1 SUMMARY OF SIMILAR OPERATIONS AND AVAILABLE PROPULSION/ POSITIONING COMPONENTS

The state-of-the-art (SOA) in submarine cable laying operations was evaluated and documented in Reference 7.1. The operations across the Norwegian Trench, representative of the SOA, have been extensively documented such that relevant technical and cost information is available. This project can be succinctly summarized as follows (References 7.12 and 7.13):

In 1976 and 1977, two 250 KV, 250 MW cables were laid across the Norwegian Trench between Kristiansand, Norway and Viborg, Denmark

Route: Length: 125 km (70 nm)
Max. Depth: 550 m (1800 ft)
Cable: O.D.: 110 mm (4.33 in) - Estimate
w(wet): 38.5 kg/m (25.8 lb/ft) - Estimate
Min. Bending Radius: <5 m (<16 ft) (Sheave dia = 10 m)
Environmental conditions encountered while laying:
Max. beam wind of 23 m/sec (45 knots)
Deployment configuration:
Cable laying barge "Skagerrak" (prior to conversion to a self-propelled barge) was positioned by four tugs and its own Schottel thrusters. Positioning and maneuvering were done manually.
Project costs:
Laying vessel: $ 9.7 M (1976)
Cable: $ 29.8 M (1977) (120$/m or 36$/ft)
Specially built cable factory: $ 9.5 M (1977)
Total project cost: $128 M (1977)
Other:
Cable transfer to turntable @ 10 m/sec (33 Fps)
Loading took two weeks
Hook-up to shore took ten hours

7.1.1. TUGS

The following companies located in Hawaii and the West Coast of the mainland were contacted for technical and cost information regarding tugs in the 1500 kw to 3000 kw (2000 HP to 4000 HP) range. This range was selected from rought-order-of-mangnitude (ROM) estimates of the environmental loads on both the bow/stern and starboard/port axis on a baseline barge exposed to Alenuihaha weather from arbitrary directions. The final analysis documented in Section 7.3 indicates thrust requirements equivalent to a combination of the thrust available from two tugs in the lower power range in addition to one or two tugs in the high end of the range.

Crowley Maritime Corporation
101 California Street, 48th Floor
San Francisco, CA 94111
(415)
Contact: Mr. Graham Fraser
Director of Corporate Engineering

Pacific Towing (Pactow) (Dillingham Subsidiary)
P.O. Box 1940
Long Beach, CA 90801
(213) 435-0171
Contact: Mr. P.B. Baldwin
Vice President, Marketing

Foss Tugs (Dillingham Subsidiary)
660 West Ewing Street
Seattle, WN 98119
(206) 281-3800
Contact: Mr. Don Duffy
Vice President for Marketing

Dillingham Tug and Barge

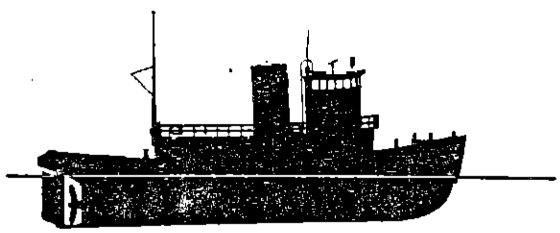
Honolulu, HI

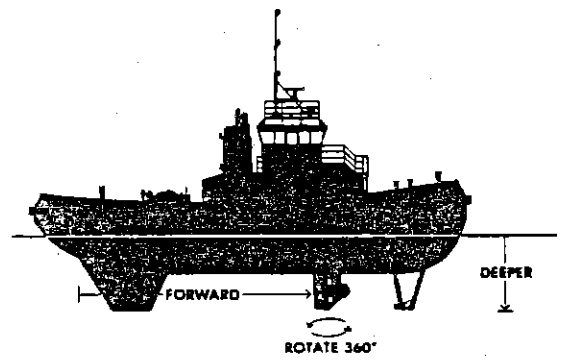
Contact: Mr. Joe Keane

Faustug Marine Corporation
Pier 15, The Embarcadero, 2nd Floor
San Francisco, CA 94111
(415) 986-1050
Contact: Mr. Louis Cohen
Chartering Manager

Figure 7.1 depicts the generic tugs available. Technical descriptions of all tugs are enclosed in Appendix and a summary of relevant information is tabulated in Table 7.2.

In brief, it appears that the Crowley Maritime Corporation has three classes of conventional tugs, totaling 14 vessels, with appropriate power (e.g., greater than 1500 kW (2000 HP)). Dillingham Tug and Barge in Hawaii also has three conventional tugs with appropriate power. However, both the Crowley and the Dillingham tugs are conventional single or twin screw tugs with or without Kort nozzles, with fixed pitch propellers and reverse direction via gear boxes. This type of tug might prove to be a liability if the tugs were to be used in a dynamic positioning mode where direction reversals might be frequent. The Pactow and Foss Tugs considered in this study are Voith-Schneider Tractor Tugs with Cycloidal Propellers providing unparalleled maneuvering capabilities. The time required to reverse thrust





Conventional Tug

Types: Utility Tug:
L < 20m (65 ft)
Harbor Tug:
20m < L < 37m
Ocean-Going Tug:
L > 37m (120 ft)

Propulsion: Single or twin screws open or ducted propellers (ducts = "Kort nozzles")

Tractor Tug

Types: Voith-Schneider Props (VSP)
Rotatable thruster types (RO)

Propulsion: Always two thrusters.

Overall length typically smaller than conventional tugs

FIGURE 7.1
GENERIC TUGBOATS

TABLE 7.2

TUGS AVAILABLE ON WEST COAST AND IN HAWAII

CONVENTIONAL TUGS

Owner	CROWLEY, San Francisco			DILLINGHAM TUG AND BARGE, Hawaii	
Class/Type	Sea Racer	Blackhawk	Daring	MANA	MALANAE
No. of Tugs	4	3	7	1	2
Operating Region	Ocean-going			Hawaii	
Cost ($)	$4500 per 24 hour day (1 month minimum) including crew and insurance. Typically, $600 additional cost for fuel @ 700 gal/day x 0.8 $/gal. Maximum fuel consumption 3000 gal/day for standard ocean crossing operations.			- $8500 per 24 hour day all included - $5500 per 24 hour standby	- $7000 per 24 hour day all included - $4500 per 24 hour standby
Bollard Power (kW/HP)	1 x 2610 (1x3500)	2 x 1232 (2x1650)	1 x 2089 (1x2800)	2 x 1120 (2x1500)	2 x 995 (2x1334)
Bollard Pull (Thrust; N/kips)	358,080 (80)	337,618 (76)	286,464 (64)	See figure quoted below from static pull test November 1983	
Thrust/Power (N/kW; lb/HP)		137 (23)		167 (28)	134 (22.5)
LOA x Beam x Draught (m)	37x9.8x4	37x10.4x4	37x9.8x4	37.5x10.4x4.8	30x9.8x3.4
Propulsion Control	Fixed Pitch Propeller Gear Box			Fixed Pitch Kurt Nozzle	Fixed Pitch
Time to Reverse Thrust	30 sec.			Assume 30 sec.	

TABLE 7.2

TUGS AVAILABLE ON WEST COAST AND IN HAWAII

TRACTOR TUGS

Owner	FAUSTUG, San Francisco		FOSS TUGS, Seattle, or PACTOW, Long Beach
Class/Type	4000 HP	4200 HP	V-S Tractor Tugs
No. of Tugs	2	6	Several
Operating Region	Ocean-going		Inner Harbor, Seattle and Long Beach
Cost ($)	$3000 per 24 hour day with crew and insurance. Fuel from $600-$2000, depending on consumption.		- $12,000 per day - 30 day minimum - new tug $4.2M
Bollard Power (kW/HP)	3000 (4000)	3130 (4200)	1 x 2610 (1 x 3500)
Bollard Pull (Thrust; N/kips)	400,338 (90)	430,000 (97)	NA
Thrust/Power (N/kW; lb/HP)	134 (22.5)	137 (23)	Assume 149 (25)
LOA x Beam x Draught (m)	28 x 10.4 x 4.8		30.5 x 11 x 4.8
Propulsion Control	Rotatable Thrusters (360° Azimuthing) with Joystick		Voith-Schneider Cycloidal Propellers with Joystick
Time to Reverse Thrust	Instantaneous		Instantaneous

with a Tractor Tug is essentially instantaneous, while conventional tugs require at least 30 seconds. The VS Tractor Tugs are included here to document the capabilities of their propulsion/positioning systems. However, at present VS Tractor Tugs (West Coast) are intended to operate in their assigned inner and outer harbor region only.

Faustug has eight ocean-going Tractor Tugs with a pair of Rotatable Thrusters (instead of VS Cycloidal Propellers) providing power in the 3000 kW to 3130 kW (4000 to 4200 HP) range and with the same exceptional maneuvering capabilities. These Rotatable (RO) Tractor Tugs can be conceptualized providing the thrust required to propell and position the baseline barge (see Section 7.3 for details) in an environment equivalent to Alenuihaha nominal conditions. However, the barge/tug attachment necessary for effective and safe operations with tugs performing as thrusters attached to the barge is yet to be designed. Furthermore, rental costs for the baseline barge and sea-going tugs potentially available to the project can be summarized as follows:

TUGS

Source	DTB (Hawaii)		Crowley* (SFO)	Faustug* (SFO)
Tug Type	Conventional		Conventional	Tractor
Power	1343 kw (1800 HP)	2240 kw (3000 HP)	2611 kw (3500 HP)	3000 kw (4000 HP)
Total Daily (24 hour) Cost (includes insurance and fuel)	$7000 (standby $4500)	$8500 (standby $5500)	$5000	$4000

*Notes:

- Transit SFO-HI-SFO $100,000
- Crowley and Faustug one month rental minimum
- A new tractor tug of 3000 kW (4000 HP) costs approximately $\$4.2 \times 10^6$ (1984)
- Rental costs reflectthe depressed market in 1984.

BARGE

Source	Zidell (Portland)	Crowley (SFO)	Remarks
Daily Cost	$4200/day	$4500/day	Short term ≤ 4 months
	$3000/day	$3000/day	Long Term ~ 1 year
Daily Insurance	NA	$425/day	
Purchase Cost	$\$5 \times 10^6$	NA	

7.1.2 THRUSTERS

The following companies provided technical information describing their thrusters:

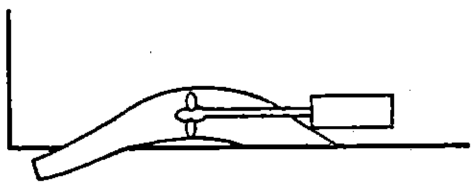
Omnithruster
Aquamaster
Elliott White Gill
Kawasaki
Schottel-Lips
Voith-Schneider

Technical summaries of each thruster are given in Tables 7.3 through 7.8 and relevant excerpts from the companies' brochures are included as Appendix . Each technical summary is intended as an overview of each product to allow intercomparison. Figure 7.2 depicts the different thruster types found today. The following parameters represent the nominal values assumed in this study:

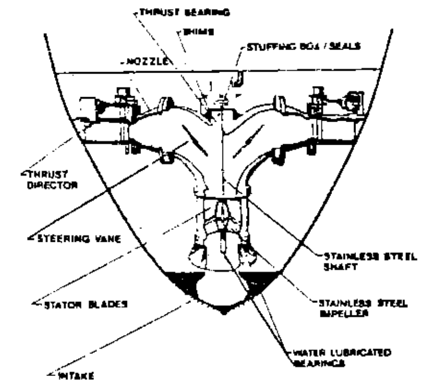
$\frac{\text{Static Thrust Delivered}}{\text{Rated Power}}$: 149 N/kW (25 lbs/HP)

$\frac{\text{Capital Cost}}{\text{Rated Power}}$: - Fixed Thrusters - 120$/kW (90$/HP)
- Rotatable Thrusters - 160$/kW (120$/HP)

$\frac{\text{Engine Cost}}{\text{Rated Power}}$ (Rotatable Thruster) : 160$/kW (120$/HP)

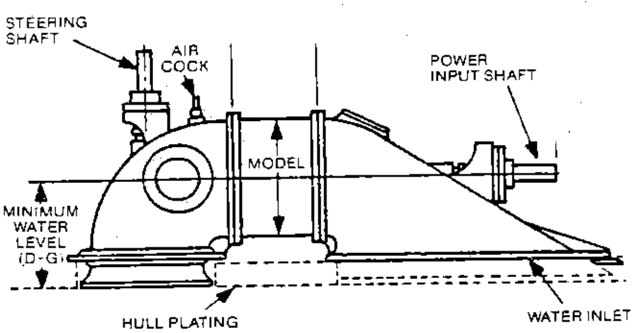


Jacuzzi-type

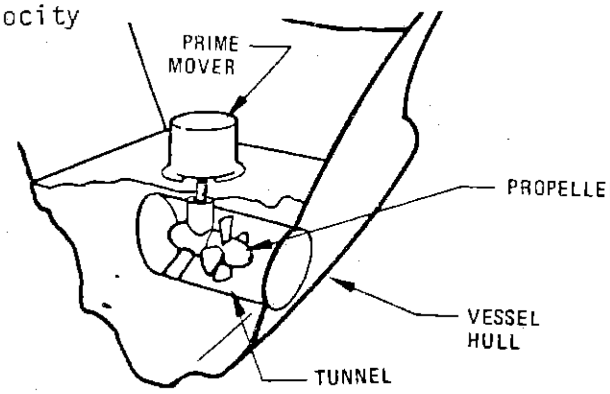


Omnithruster type

<u>Waterjets</u> (high velocity

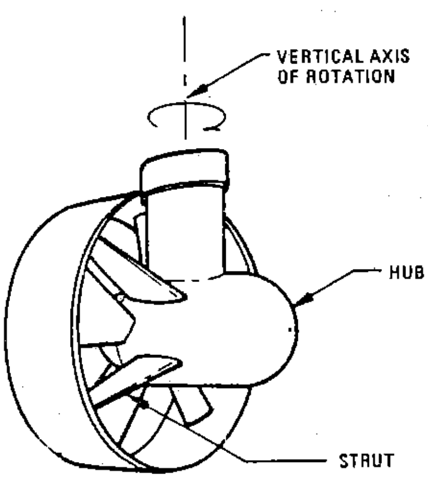


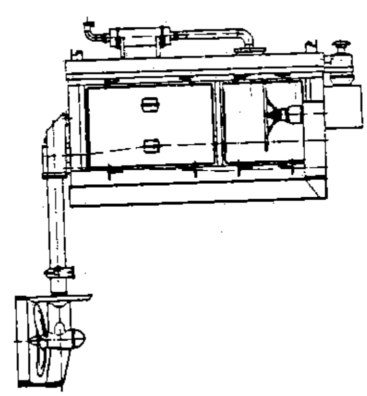
Elliott White Gill-type

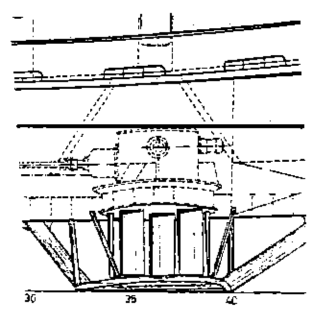


Transverse thruster

<u>Waterpumps</u> (low velocity)







<u>L-thrusters</u>

- with or without kort nozzles
- containerized or not
- 360° rotatable or fixed

<u>Z-thrusters</u>

- same comments as L-thrusters
- typically, deck mounted with horizontal engine and less power than L-thruster

<u>VSP</u>

FIGURE 7.2
THRUSTER TYPES

TABLE 7.3

OMNITHRUSTER THRUSTERS

Description:	Maneuvering and positioning system. Single inlet, bi-directional thruster developing thrust via high velocity, lateral water jets. Limited fore and aft thrust capability.
Power Range:	19 to 1120 kW (25 to 1500 HP)
Thrust/Power:	95 to 143 N/kW (16 to 24 lbs/HP)
wt @ 746 kW:	80,070 N (18,000 lbs)
Dims @ 746 kW:	H x B x L 4 m x 3 m x 2 m (13.3 ft x 9.8 ft x 6.7 ft)
Main Engine:	Diesel or electric
Control Rates:	Not available
Cost:	Not available
Comments:	Limited suitability for these reasons: • small HP maximum 1120 kW (1500 HP) • difficult to install and operate on a barge due to lengthy water pipe requirements. System is designed for use in bow or stern of regular ship shapes.
Address:	Mrs. Violet J. Winslow Director, Marketing Administration Omnithruster, Inc. 9515 Sorensen Avenue Santa Fe Springs, CA 90670

TABLE 7.4

AQUAMASTER THRUSTER

Description:	360° rotatable propulsion unit, retractable or non-retractable, shrouded or non-shrouded fixed pitch propeller, available in containerized form.
Power Range:	90 to 3000 kW (120 to 4000 HP)
Thrust/Power:	185 - 197 N/kW (31 - 33 lbs/HP) with Kort nozzle
746 kW specs: weight:	73,400 N (16,500 lbs)
dimensions:	H x B x L 4 m min to 8 m max x 2.8 m x 2.8 m (13.1 ft min to 26.2ft max x 9.3 ft x 9.3 ft)
Main Engine:	Diesel or electric, for single unit installation DC-electric preferred for ease of thrust control.
Control Rates:	Steering: 15.7 deg/sec

Cost:

Power Range	$ x 1000
1120 - 1450 kW (1500 - 2000 HP)	175
1450 - 1790 kW (2000 - 2400 HP)	250
1865 - 3000 kW (2500 - 4000 HP)	450

Comments: Suitable power range, limited by fixed pitch propeller (use DC electric motor to compensate).

Address:

Mr. Richard Todd
Aquamaster, Inc.
4125 9th Avenue, N.W.
Seattle, WN 98107
(206) 782-2931

TABLE 7.5

ELLIOTT WHITE GILL THRUSTERS

Description:	Propulsion unit with 360° rotatable water outlet. No protrusion beyond the hull lines of a vessel. Can be driven by vertical or horizontal shafts or over V-belts.
Power Range:	42 kW to 1640 kW (56 HP to 2200 HP)
Thrust/Power:	83 to 101 N/kW (14 to 17 lbs/HP) See note above.
Weight @ 746 kW:	90,210 N (20,280 lbs)
Dimensions @ 746 kW:	H x B x L 3.3 m x 2.1 m x 2.1 m (10.8 ft x 6.9 ft x 6.9 ft)
Main Engine:	Diesel or electric

Cost:

MODEL T3

No.	Power	Thrust (lbs)	Thrust/Power	Cost	Panel
50	833 kW 1117 HP	18,730	100 N/kW (16.8 lb/HP)	$167,000	$20,000
60	1253 kW 1680 HP	27,430	97 N/kW (16.3)	$264,000	$22,500
70	1633 kW 2189 HP	37,730	103 N/kW (17.2)	$328,500	$28,000

Control Rates:	Not provided
Comments:	System has been used on cable layer "RECORDER." Low propulsive efficiency.

Address:

Mr. Jack B. Tarbert
Sales & Contract Administrator
Elliott White Gill Thruster
1809 Sheridan Avenue
Springfield, OH 45501
(513) 324-4191

<u>OR</u>:

Mr. Rick Whitney
Whitney Associates, Inc.
P.O. Box 22160
San Diego, CA 92122
(619) 481-3222

TABLE 7.6
KAWASAKI THRUSTERS

Description:	360° rotatable propulsion unit, retractable or non-retractable, shrouded fixed pitch or controllable pitch propeller, available in containerized form.
Power Range:	290 - 4551 kW (390 - 6100 HP)
Thrust/Power:	137 to 143 N/kW (23 to 24 lbs/HP)
Weight @ 746 kW:	82,736 N (18,600 lbs)
Dimensions @ 746 kW:	H x B x L: 3.7 m x 1.6 m x 2.2 m (12.3 ft x 5.2 ft x 7.2 ft) regular thruster 9.8 m x 3.4 m x 3.4 m (32.2 ft x 11.2 ft x 11.2 ft) container thruster
Main Engine:	Diesel or electric
Control Speeds:	Steering: 18 deg/sec; Pitch: 5 deg/sec

Cost:

Power	Thrust/Power	$/kW	
1492 kW (2000 HP)	143 N/kW	154$/kW	• FOB Kobe, Japan
1805 kW (2420)	or	154$/kW	• Includes remote control stand
2150 kW (2880)	24 lbs/HP	151$/kW	• @ 250yen/$
2753 kW (3690)		150$/kW	• 7 mos. lead time
3150 kW (4220)		155$/kW	

Comments: Suitable system, company has experience in offshore DP applications.

Address:
Mr. K. Sakaguchi
Manager of Marine Sales
Kawasaki Heavy Industries, Ltd.
601 Jefferson Street, Suite 3670
Houston, TX 77002
(713) 654-8981

TABLE 7.7

SCHOTTEL-LIPS THRUSTERS

Description:	360° rotatable propulsion unit, retractable or non-retractable, shrouded fixed pitch or controllable pitch propeller, available in containerized form.
Power Range:	477 kW to 4476 kW (640 to 6000 HP)
Thrust/Power:	167 to 190 N/kW (28 to 32 lbs/HP)
Wt @ 746 kW:	102,442 N (23,030 lbs)
Dimensions @ 746 kW:	H x B x L 4.3 m x 2.6 m x 2.2 m (14 ft x 8.5 ft x 7.1 ft) regular thruster 10.6 m x 3.3 m x 3.3 m (34.8 ft x 10.8 ft x 10.8 ft) container thruster
Main Engine:	Diesel or electric
Control Speeds:	Not provided

Cost:

	Cost (FOB Holland)		
Power	Steerable	Non-Steerable	DP Interface (optional
2126 kW (2850 HP)	$500k	$340k	$96k
3357 kW (4500)	$624k	$420k	$150k

Comments:	Suitable system, many options, company has experience in offshore DP applications. System selected for SKAGERRAK.
Address:	Mr. Henning D. Hansen Manager, Engineering Sales Schottel of America, Inc. 8375 N.W. 56th Street Miami, FL 33166 (305) 592-7350

TABLE 7.8

VOITH-SCHNEIDER PROPELLERS

Description:	Vertical axis cycloidal propeller
Power Range:	150 kW to 3000 kW (200 HP to 4000 HP)
Thrust/Power	149 N/kW (25 lbs/HP)
Wt @ 746 kW:	130,332 N (29,300 lbs), includes engine
Dimensions @ 746 kW:	H x B x L 3.1 m x 2.8 m x 2.8 m (10.2 ft x 9.2 ft x 9.2 ft)
Main Engine:	Diesel or electric
Control Speeds:	- 7 secs from 0 to full thrust - 14 secs for complete thrust reversal, full to full - intermediate direction change near instantaneous
Cost:	Cost is proportional to weight by German law, - 2 x 1120 kW (2 x 1500 HP) including engines: US$755,000 @ 2.65 DM/$ - 2 x 1500 kW (2 x 2000 HP) including engines: US$1,000,000 @ 2.65 DM/$
Comments:	Excellent maneuverability, very sophisticated system. Note that costs quoted include engine, i.e., 335 $/kW (250$/HP) where roughly half the cost is for engines.
Address:	Mr. Eli Shaprut Sales Manager Voith-Schneider America, Inc. 159 Great Neck Road New York, New York 11021 (516) 466-5755

7.2 CONCEPTUAL PROPULSION/POSITIONING CONFIGURATIONS

The alternatives to be discussed in this section are grouped according to barge propulsion system. First, propelling and positioning a barge relying on tugs only is considered. Second, partially propelled barge alternatives will be considered. And, third, self-propelled/positioned barge alternatives are described. Power requirements and thrust vectors are from Section 7.3 as follows:

- system must provide a thrust of 651 kN (146 kips) in the barge longitudinal axis; and
- system must also provide a thrust of 222 kN (50 kips) in the starboard direction and 222 kN (50 kips) in the port direction and combined yaw moment about the vessel c.g. of 8,135 kN-m (6000 kip-ft).

This can be accomplished with two generic systems as follows:

- Two rotatable thrusters (fully azimuthing) rated at 333.6 kN (75 kips) each for a total power of 4476 kW (6000 HP) with an effective coupling arm of 24m (80 feet).
- A system providing 651 kN (146 kips) of thrust in the longitudinal axis via one or two fixed (longitudinal) thrusters and 222 kN (50 kips) of thrust in both the starboard and port directions with an effective coupling arm of 37 m (120 feet) and a total combined power of 7350 kW (9851 HP)

[Figure 7.5 depicts systems meeting these requirements]

As stated above throughout this report it is assumed that tugs can somehow be attached to the baseline barge to provide thrust equivalent to a fixed thruster at their rated power. That is, the design of Tug/Barge connections is beyond the scope of this conceptual study.

7.2.1 BASELINE BARGE WITH TUGS

Here, the barge only has enough power on board to drive the cable-handling equipment and other auxiliaries. Propulsive and stationkeeping (positioning) power are entirely supplied by tugs. A minimum of three fixed thruster-axis tugs (conventional single or twin-screw tugs with rudders inactive) or two rotatable thruster tugs (VSP or RO-thrusters) are considered. Several barge/tug(s) arrangements can be conceptualized. Three concepts shown in Figure 7.3 depict yet to be designed "connectors." However, at present we do not consider that the cost effective design of such connectors to operate under the baseline environment of 2.4 m (8 ft) significant seas is feasible. Moreover, based solely upon actual experience (References 7.15, 7.16, 7.17

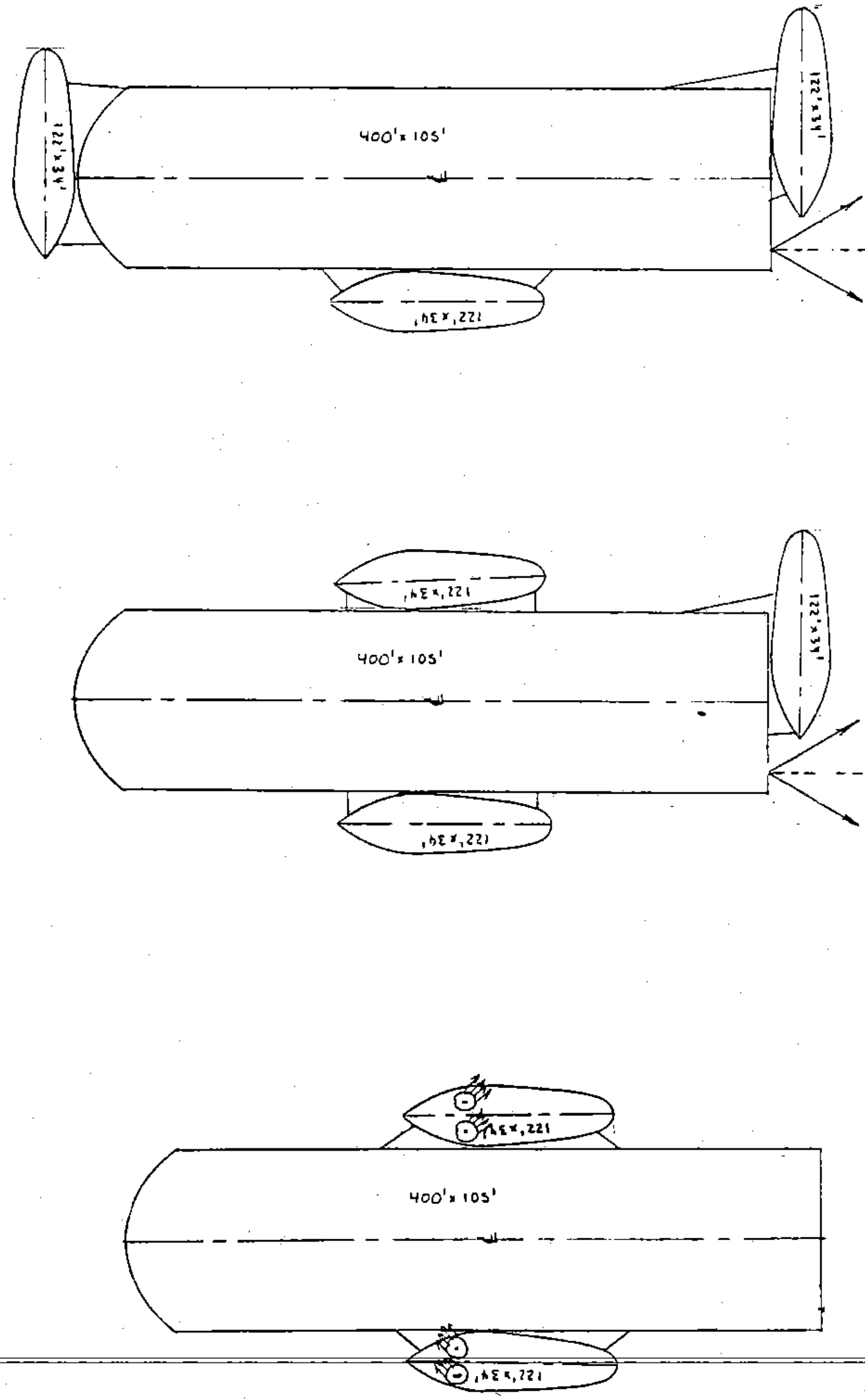


Figure 7.3 Barge/Tug(s) Conceptual Arrangements

7.18 and 7.26) and without the need of detailed analysis we do not recommend the use of only tugs to provide thrust to the baseline barge in a prescribed direction under sea conditions equivalent to significant heights larger than ~ 1.2 m (4 ft). A summary of the generic Tug/Barge attachment concepts is given in Section 7.2.4.

7.2.2 MODIFIED BARGE WITH FIXED THRUSTERS AND TUG(S)

It is assumed that the baseline barge has been equipped with thrusters partially providing the thrust vectors required for a specific operation. As summarized above, the power requirements for the commercial system are such that the use of this generic concept is not attractive. However, for the test lay (or HDWC project) it might be an option because of the short duration of the project. That is, this concept represents a cost effective compromise between a high capital cost of an entirely self-propelled barge and the relatively higher operational costs associated with the use of tugs.

Two of the many conceptual arrangements are shown in Figure 7.4. The arrangement depicting two lateral thrusters with a tug alongside (could also depict tug towing barge) providing the required longitudinal-axis thrust could be adapted to the HDWC project pending the definition of test objectives.

7.2.3 SELF-PROPELLED/POSITIONED BARGE

A self-propelled barge entirely relies on its own propulsion to position itself along the cable route. The internal thruster arrangement could consist of a minimum of three fixed thrusters or two rotatable thrusters. However, since two rotatable thrusters are more cost effective, such a configuration is a more likely candidate.

Conceptual thruster installations for such application and the nominal geometry assumed for the mathematical modeling are depicted in Figure 7.5.

7.2.4 TUG AND BARGE ATTACHMENT CONCEPTS

There are several ways of attaching tugs to a barge in a pushing or towing situation. The need to exert thrust in all directions precludes the use of loose towing lines that only act under tension. There are two generic methods for securing a barge to a tug that allow the tug to push as well as to pull a barge. One method is for the tugs to make fast alongside the barge using tow lines; the other is a linkage system, called "Sea-Link," permitting the decoupling of tug and barge roll, heave and pitch.

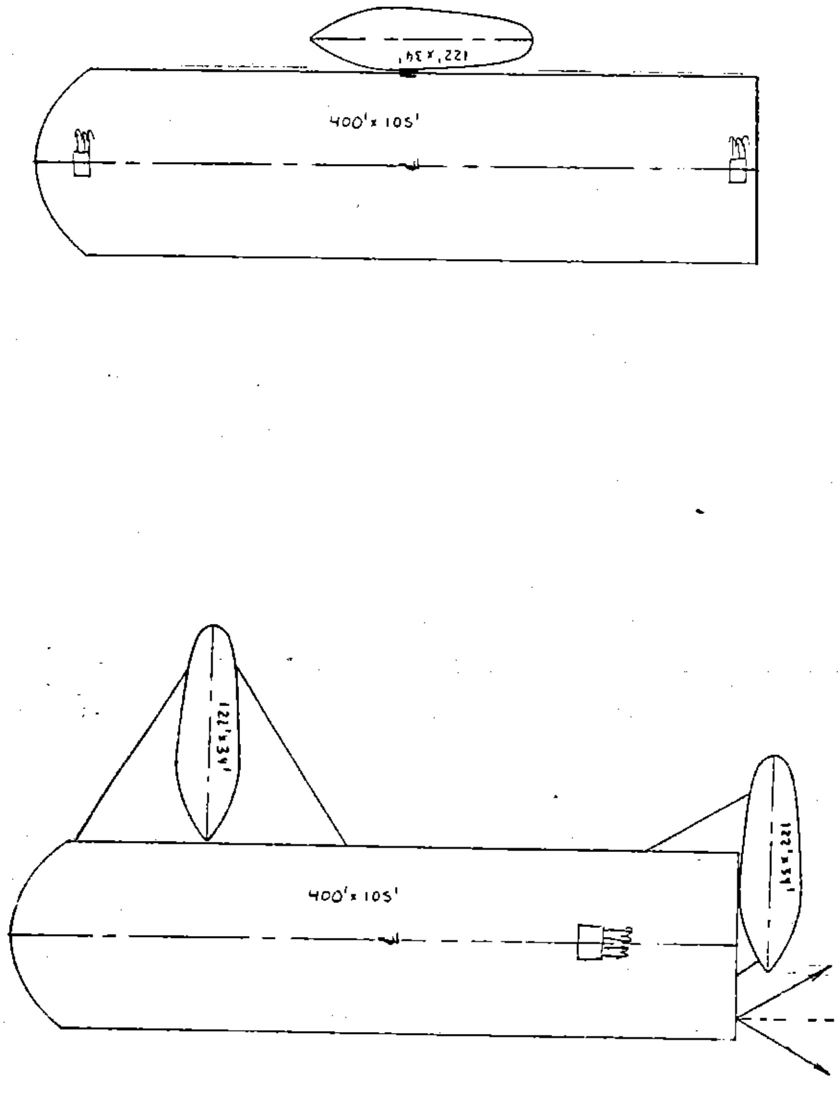
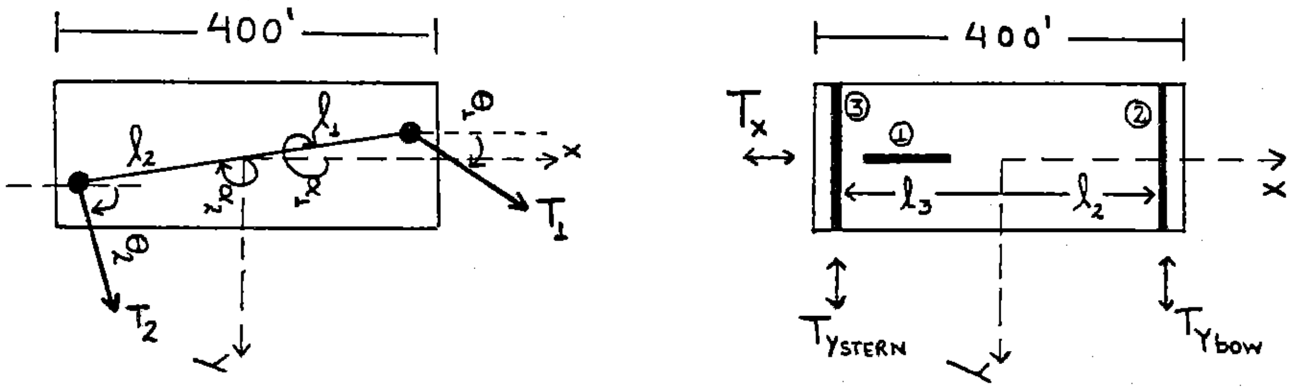


Figure 7.4 Barge with Partial Propulsion Assisted by Tug(s)

ROTATABLE THRUSTERS | FIXED THRUSTERS



Geometry	Geometry
$l_1 = l_2 = 180$ ft	$l_2 = 190$ ft
$\alpha_1 = -10^o$	$l_3 = -190$ ft
$\alpha_2 = 170^o$	$[l_1 = 0]$

Thrust (Power) Required

- Alenuihaha Baseline Weather ----------------------------------

  Ref: Tables 7.9 and 7.10

  $T_1 \leq 71.6$ Kips (2864 HP)

  $T_2 \leq 71.2$ Kips (2848 HP)

  $T_x \leq 64.7$ Kips (2588 HP)

  $T_{ybow} \leq 35.9$ Kips (1436 HP)

  $T_{ystern} \leq 48$ Kips (1920 HP)

- "Extreme" Operational--

  Ref: Colinear Head Wind, Current and Seas of Alenuihaha Magnitude

  $T_1 = T_2 = 73.2$ Kips (2928 HP)

  $T_x = 146.4$ Kips (5856 HP)

  $T_{ybow} = T_{ystern} = 0$

Figure 7.5 Modeled Geometry for Baseline Barge with Fixed or Rotatable Thrusters

7.2.4.1 "On the Hip"

When moving a barge "on the hip," a tug or several tugs will make fast on the barge via towlines at similar locations as depicted in Figures 7.3 and 7.4 The conceptual-connections between tugs and barge shown in those figures are made to resemble lines, even though these connections are yet to be designed. The idea is to continue the analysis assuming that if a tug/barge system is cost competitive with the self-contained barge, then one would have to consider the feasibility of such connections. To select the location of each tug, one must consider the interference of a tug with on-deck operations on the barge; and the magnitude of relative motion between tugs and barge at an attachment point in a seaway. The attachment locations should be chosen to minimize the relative motions.

This method of joining tugs and barge has the serious drawback that it is only advisable to use in good weather conditions, nominally wave heights of less than 1.2 meters. In any case, working lines should be doubled and heavy fendering used as damage can be expected. One method to avoid this problem might be a piece of hardware called "Sea-Link."

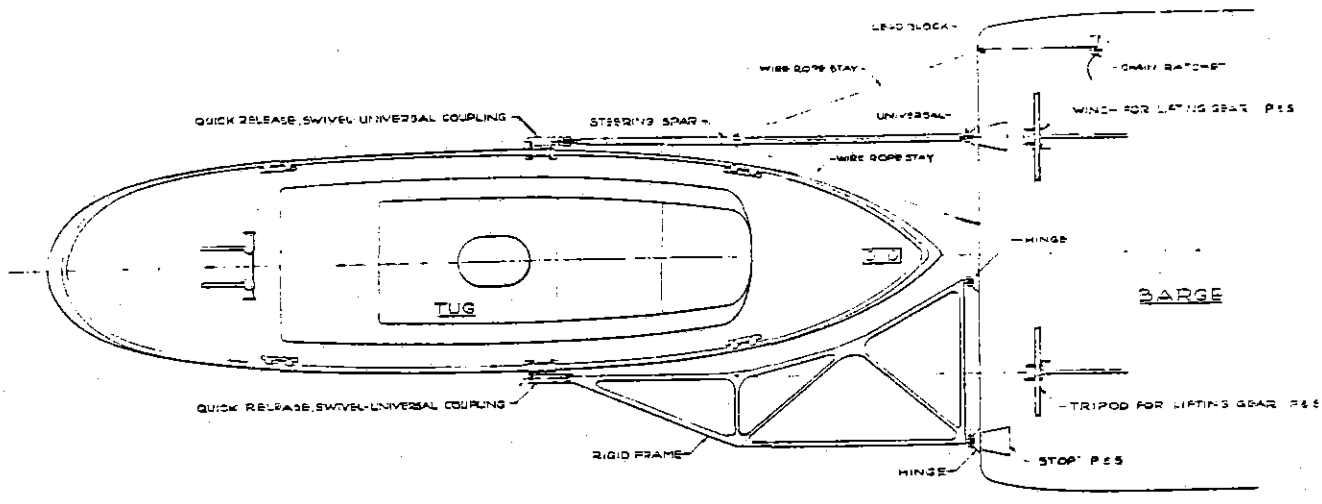
7.2.4.2 Sea Link

Figure 7.6 shows the elements of the Sea-Link attachment system. As can be seen, barge pitch, heave and roll are decoupled from the tug motion. However, it has only been successfully utilized with tugs of 1500 kW (2000 HP) and barges of about 3000 t DWT. A larger system will require elaborate design of a strong and light attachment structure requiring precise machinery of the bearings.

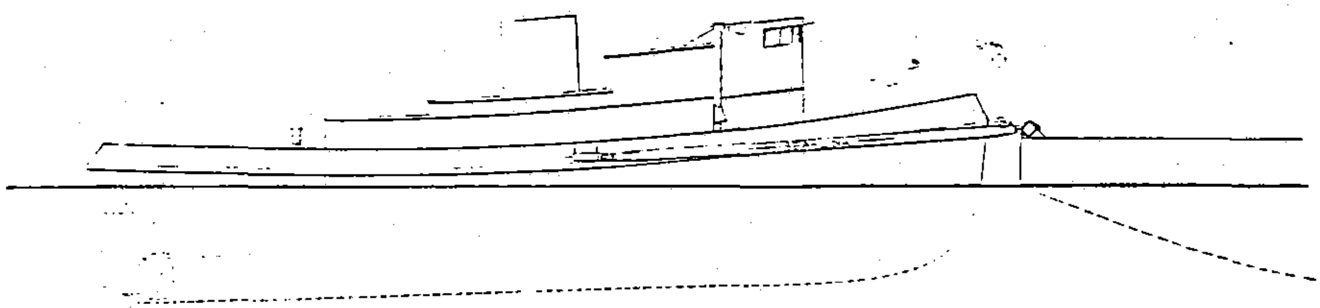
The conceptual connections between barge and tugs depicted in Figures 7.3, 7.4 and 7.6 have been presented because they might be of use to the design of a system for the test lay in the Alenuihaha Channel (i.e., the HDWC Project instead of the Commercial Project). The following cost differential comparison coupled to the superior maneuverability of a self-contained barge system leads us to conclude that a barge solely assisted by tugs should not be considered as an alternative for the Commercial System.

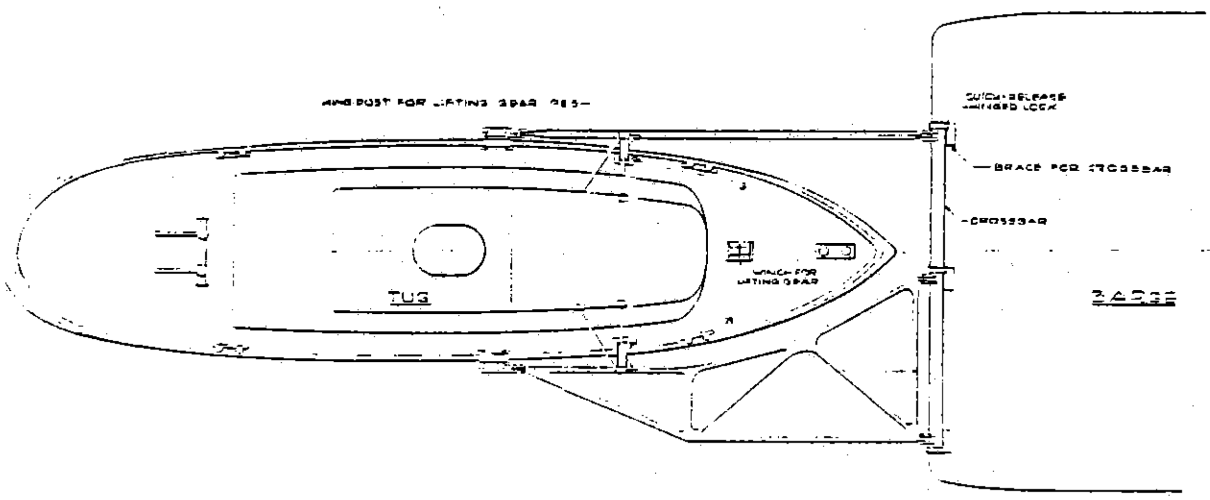
7.2.5 COST DIFFERENTIAL COMPARISON

Three power cables will be deployed in addition to a ground return cable. The cable deployment system has to be capable of taking on the cable sections of 100 km in length from shore, and deploying it along the approximately 250 km (135 nm) route. The cable deployment phase of the Commercial Project can be separated into four phases relevant to the propulsion and positioning aspects of the laying vessel as follows:



Sea-Link, barge mounted





Sea-Link arrangement, tug mounted

Figure 7.6 Sea-Link Arrangement

1. Taking on the cable from shore and transitting to the cable laying starting point;
2. Hook-up of cable to shore point;
3. Actual cable laying, including splicing of cable;
4. Retrieval of damaged cable.

The following values have been assumed for each cable leg to represent typical durations (References 7.11, 7.12 and 7.13):

Phase 1:	Transit from Italy:	42 days (18,520 km @ 5.1 m/sec)
	Transit from West Coast:	10 days (4,260 km @ 5.1 m/sec)
	Transit within Hawaii:	0.5 days (220 km @ 5.1 m/sec)
	Taking on Cable:	15 days (@ 10 m/min)
Phase 2:	Hook-up:	2 days
Phase 3:	Cable Laying:	30 days
Phase 4:	Retrieval of Damaged Cable:	Previous operations in shallower water and shorter routes in the order of weeks.

It must be emphasized that the 30 days assumed for laying cable along the 250 km route (Phase 3 only) represent an upper limit utilized to evaluate the costs associated with the rental of propulsion/positioning equipment (e.g., Tugs) for each leg.

The costs associated with the following systems were considered to establish the cost differential between the use of tugs or thrusters to provide the propulsion and positioning requirements listed at the beginning of Section 7.2. Once more, it must be emphasized that tugs are assumed to somehow perform as fixed thrusters (see Figure 7.5):

System A
- Baseline Barge
- 2 x 2240 kW Ro-Thrusters
- Engines for Thrusters
- Installation of Thrusters

System B:
- Baseline Barge
- 2 x 2240 kW (3000 HP) Tugs in the longitudinal axis
- 1 x 1490 kW (2000 HP) Tug attached as a bow "thruster"
- 1 x 1490 kW (2000 HP) Tug attached as a stern "thruster"
- Design/fabrication of Tug-Barge connection.

Operations
- Power Cable Laying - 30 days/cable x 3 cables = 90 days
- Ground Cable Laying - 15 days

Therefore, total number of days providing propulsion and positioning could be as high as 105 days over a four-year period.

To estimate cost differential, exclude components in common (i.e., Barge) and assume that present cost differential between mainland and Hawaii tugs is offset by transit cost such that the following partial cost would be incurred in today's dollars:

- Capital investment for System A (excluding installation):
  4476 kW x (160$/kW + 160$/kW) = $1.43M
  (Purchase Thruster) (Purchase Engine)
- Operating investment for System B (excluding fabrication):
  105 days x [2 x $8500 + 2 x $7000] = $3.26M

The resulting cost differential has to be evaluated by comparing the cost of installing thrusters against the costs of designing and fabricating several Tug/Barge connectors. The installation of Thrusters will cost less than $0.7M (assuming installation costs equal purchase costs as a conservative upper limit) such that System A should at least be $ 1.1M less expensive. Therefore, we are recommending System A as a baseline or input to the next phase of the design. Moreover, the baseline barge with two Rotatable Thrusters for a total of 4476 kW (6000 HP) can be designed to provide a means of transporting the cable from the factory to Hawaii.

Costs associated with the HDWC Project (Test Lay) should not be estimated until test objectives are defined. That is, costs associated with the different propulsion/positioning systems considered in this study are not sufficient information until the Program Office defines whether or not testing the propulsion system recommended for the commercial system should be modeled.

7.3 ENVIRONMENTAL AND TASK-RELATED EQUILIBRIUM (STATIC) FORCES AND MOMENTS ON THE CABLE LAYING BARGE

The analytical model of the environmental and task-related steady forces and moments acting on the cable-laying barge is presented in this section. The equilibrium or steady components of wind and wave-drift forces and yaw moments and the drag force and yaw moment due to the relative velocity between the water and vessel are considered. The task-related loads due to the horizontal components of steady cable tension at the vessel interphase are also modeled. The resulting loads are balanced by means of fixed and/or rotatable thrusters. In this context it is assumed that tugs behave like fixed thrusters.

Figure 7.7 depicts the reference axes and notation utilized in the development of the equilibrium model. All environmental parameters are defined with respect to coordinates fixed with the earth and the resulting forces, and yaw moments are projected on the ship axes. The slow dynamic components of surge, sway and yaw motions excited by forces of relatively large time scale (i.e., greater than ~ 30 sec.) have been neglected. It must be emphasized that as the design progresses beyond the conceptual level the dynamic (loads) must be incorporated into the design of an integrated control system. For example, the slowly oscillating component of wave-drift forces for the baseline barge and environment is equivalent to a periodic force of twice the magnitude of the mean component with a period of in the order of 40 to 150 sec. Similarly, wind gusts can amount to increases in wind velocity by a factor of 1.5 (wind loads increased by a factor of 2.25) and of 1 to 2 minute durations.

7.3.1 STEADY WIND LOADS

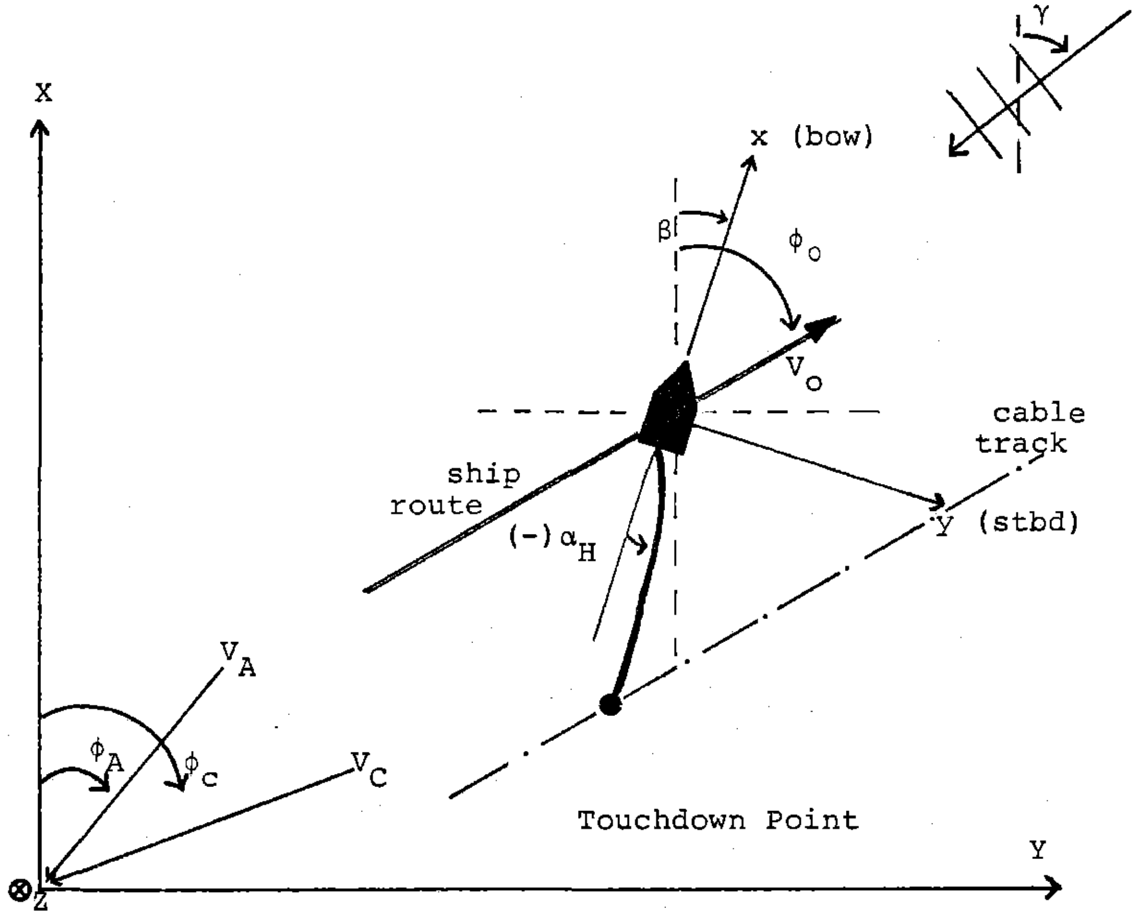
The standard representation of wind loads uses a typical velocity-square law. Some extensive and sophisticated analyses have been published on the question of non-dimensional drag coefficients and shape functions (References 7.5 and 7.6). However, the cable-laying vessel under consideration is primarily loaded from current, wave and task-related forces so that it does not seem reasonable to resort to very refined models, particularly when some parameters are only roughly estimated (e.g., projected areas). A smiplified approach, with typical values of the drag coefficients chosen in agreement with Ref. 7.5 and 7.6 is used instead.

The horizontal components of steady wind forces and the yaw moment are modeled as follows:

$$F_{Ax} = -K_{Ax} \cos(\phi_A - \beta) V_A^2$$

$$F_{Ay} = -K_{Ay} \sin(\phi_A - \beta) V_A^2$$

$$M_A = -K_{Ay} \sin^2(\phi_A - \beta) V_A^2$$



Key:

X, Y, Z : axes fixed with the Earth and pointing, respectively, North, East and downward.

x, y, z : axes fixed with the ship.

β : steady heading angle.

ϕ_A : angle of wind relative to reference axes (Note: environment is defined towards direction of propagation).

ϕ_C : angle of current relative to reference axes.

V_A : wind velocity.

V_C : current velocity.

V_o : steady forward velocity defining ship route.

ϕ_o : angle of ship route (actual track).

γ : angle of wave propagation relative to reference axis.

Figure 7.7 Reference Axes for Equilibrium (Static) Model

In these equations, trigonometric terms represent idealized shape functions. Moreover, the absolute wind speed is used because it is assumed to dominate the ship speed: $V_A >> V_O$. The coefficients K_{Ax}, and K_{Ay} and K_{Az} are defined as follows:

$$K_{Ax} = \frac{1}{2} \rho_a C_{Ax} A_x$$

$$K_{Ay} = \frac{1}{2} \rho_a C_{Ay} A_y$$

$$K_{Az} = \frac{1}{2} \rho_a C_{Az} A_y L$$

ρ_a = density of air

A_x = projected front area

A_y = projected side area

L = length of vessel

The non-dimensional drag coefficients C_{Ax}, C_{Ay} and C_{Az} are subsequently taken as:

$C_{Ax} = 0.80$

$C_{Ay} = 0.80$

$C_{Az} = 0.10$

Projected areas are estimated as follows for the baseline barge:

$$A_x = 30.5 \times (6.1 - 3.05 + 1.82) = 148.6 \text{ m}^2 \text{ (1600 ft}^2)$$

$$A_y = 122 \times (6.1 - 3.05 + 1.82) = 594.6 \text{ m}^2 \text{ (6400 ft}^2)$$

in these formulas, 1.82 m (6 ft) account for the equipment and superstructure above the deck.

7.3.2 STEADY CURRENT LOADS

When dealing with current loads, the situation is somewhat more complex than with wind loads. The relative fluid velocity resulting from surface current and vessel speed must be considered. Thus, the following definitions are necessary:

$$V_R = (V_c^2 + V_o^2 + 2V_oV_c \cos(\phi_c - \phi_o))^{1/2}$$

$$\alpha_o = \tan^{-1} \frac{V_c \sin(\phi_c-\beta) + V_o \sin(\phi_o-\beta)}{V_c \cos(\phi_c-\beta) + V_o \cos(\phi_o-\beta)}$$

Moreover, the single equations used for wind loads implicitly imply that flow separation occurs and that, consequently, drag coefficients do not depend upon the Reynolds number. This approach is still valid in the case of yaw and sway. Therefore, we can write:

$$F_{cy} = -K_{cy} \sin \alpha_o V_R^2$$

$$M_c = -K_{cz} \sin(2\alpha_o)V_R^2$$

where,

$$K_{cy} = \frac{1}{2} \rho C_{cy}LT$$

$$K_{cz} = \frac{1}{2} \rho C_{cz}L^2T$$

In this case, ρ represents the density of water and T the draught of the vessel. Typical values are chosen for C_{cy} and C_{cz} in agreement with References 7.5 and 7.7 as follows.

$$C_{cy} = 0.90$$

$$C_{cz} = 0.10$$

The situation is not so simple for the longitudinal force because viscous effects play a significant role. The model used here is based on Reference 7.4 The total resistance, $-F_{cx}$, is written as the sum of a frictional term, R_F and a residual term R_R as follows:

$$R_F = C_FS(V_R \cos \alpha_o)^{1.825}$$

$$R_R = C_RBTC_B(V_R \cos \alpha_o)^2$$

In these formulas, B and $\mathcal{S}$ represent the beam and wetted surface of the vessel, respectively, whereas C_B is the block coefficient. $\mathcal{S}$ is defined by the following empirical relation:

$$\mathcal{S} = 0.9206\ L^*B + 1.669\ L^*T$$

where, L* is the length between perpendiculars (LBP); and

$$C_R = 4.226 \quad N\text{-}sec^2/m^4 \quad (0.0082\ lb\text{-}sec^2/ft^4)$$

for $(V_R \cos \alpha_o) < 4.1$ m/sec (8 knts)

$$C_F = 0.00876$$

for L* = 380 ft, $\mathcal{S}$ in ft^2 and V_R in knots; or

$$C_F = 1.41$$

for L* = 116 m, $\mathcal{S}$ in m^2 and V_R in m/sec.

7.3.3 STEADY WAVE DRIFT FORCES AND MOMENTS

When an object interferes with an incident wave field, it slowly drifts as a blocking of wave-momentum transfer occurs. An accurate modelling of these loads is extremely difficult and requires, at least, the solution of the diffraction boundary-value problem. This task is well beyond the scope of the present analysis, and a rather crude method for assessing steady wave drift forces and moments has been chosen.

7.3.3.1 Sea-Induced Loads

At first, a wave spectrum $S(\omega)$ is selected. The classical two-parameter Bretschneider model defined by significant wave height H_S and peak frequency ω_o is utilized (Ref. 7.1). Next, the spectrum is corrected for barge speed as given in Reference 7.1. In the following, it is assumed that these corrections have been made and the original notation $(\omega, S(\omega))$ is used. Then, drift forces are estimated as in References 7.5, 7.8, and 7.9 as follows:

$$F_{WD_x} = \frac{-\rho g B H_S^2}{16} R^2(\bar{k}T) \cos^2(\gamma-\beta)\ \mathrm{sign}\,(\cos(\gamma-\beta))$$

$$F_{WD_y} = \frac{-\rho g L^* H_S^2}{16} R^2(\bar{k}T) \sin^2(\gamma-\beta)\ \mathrm{sign}\,(\sin(\gamma-\beta))$$

R is an empirical drift force coefficient related to the mean wavenumber $\bar{K}$ as shown in Figure 7.8 for a body cross-section of 2.5.

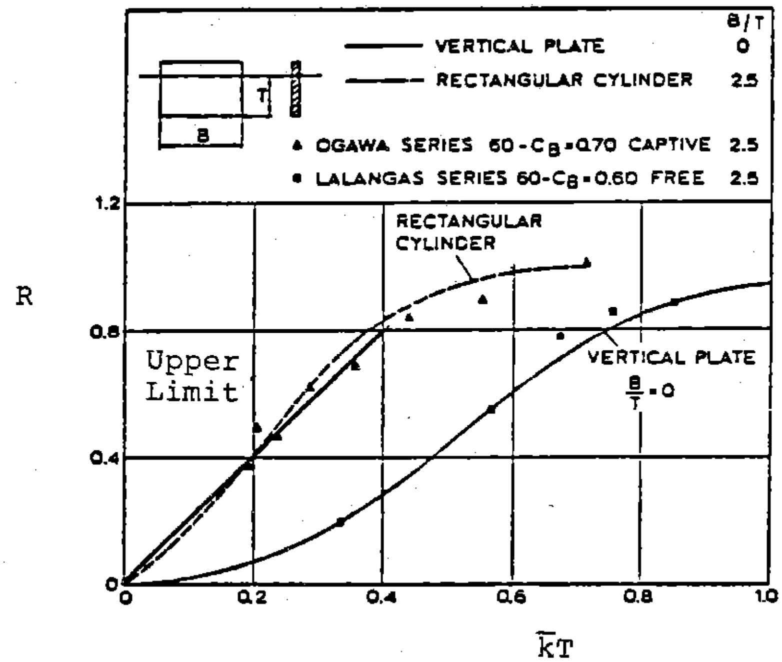


Figure 7.8 Mean Drift Force Coefficient

For deep-water waves:

$$\bar{k} = \frac{\bar{\omega}^2}{g}$$

where,

$$\bar{\omega} = \frac{\int_0^\infty \omega S(\omega)\, d\omega}{\int_0^\infty S(\omega)\, d\omega}$$

With the Bretschneider spectrum unaltered to account for forward-speed effects, $\bar{\omega}$ is related to the spectral peak frequency as follows:

$$\bar{\omega} = 1.296\ \omega_o$$

In the case of the yaw drift moment, an equivalent formula is derived based on References 7.8 and 7.9, as follows.

$$M_{WD} = \frac{-\rho g L^2 H_S}{16} f\left(\frac{\overline{\lambda}}{L^*}\right) \sin 2(\gamma-\beta)$$

where,

$$\overline{\lambda} = \frac{2\pi}{\overline{k}} \text{ ; and}$$

$$f\left(\frac{\overline{\lambda}}{L^*}\right) = 0 \qquad \text{for} \quad \frac{\overline{\lambda}}{L^*} \leq 0.25$$

$$f\left(\frac{\overline{\lambda}}{L^*}\right) = 0.16\left(\frac{\overline{\lambda}}{L^*} - 0.25\right) \qquad \text{for } 0.25 \leq \frac{\overline{\lambda}}{L^*} \leq 0.5$$

$$f\left(\frac{\overline{\lambda}}{L^*}\right) = 0.04 - 0.04\left(\frac{\overline{\lambda}}{L^*} - 0.5\right) \qquad \text{for } 0.5 \leq \frac{\overline{\lambda}}{L^*} \leq 1.25$$

$$f\left(\frac{\overline{\lambda}}{L^*}\right) = 0.01 \qquad \text{for } 1.25 \leq \frac{\overline{\lambda}}{L^*}$$

7.3.3.2 Swell-Induced Loads

Swell is treated as a single sinusoidal wave-train defined by H_{SW}, ω_{SW} and γ_{SW}. As in the case of seas, ω_{SW} is replaced by the frequency of encounter and the following loads must be added to the values defined above:

$$\Delta F_{WD_X} = \frac{-\rho g\ B\ H_{SW}^2}{8} R^2(k_{SW}T) \cos^2(\gamma_{SW} - \beta) \operatorname{sign}(\cos(\gamma_{SW} - \beta))$$

$$\Delta F_{WD_y} = \frac{-\rho g \; L^* H_{SW}^2}{8} R^2(k_{SW}T) \sin^2(\gamma_{SW} - \beta) \; \text{sign}(\sin(\gamma_{SW} - \beta))$$

$$\Delta M_{WD} = \frac{-\rho g \; L^* H_{SW}^2}{8} f \left(\frac{\lambda SW}{L^*}\right) \sin 2(\gamma_{SW} - \beta)$$

7.3.4 TASK-RELATED LOADS

Task-related loads consist of the forces and moments applied on the vessel by the cable during laying operations. To determine these loads, it is necessary to know the cable tension and angles of attack at the attachment between cable and barge.

7.3.4.1 Tension Magnitude Along the Cable

The present model is based on References 7.1 and 7.2. If centrifugal forces, tangential drag along the cable and dynamic effects are neglected, tension magnitude as a function of the vertical coordinate Z is given by:

$$T(Z) = w\,(h-Z) + T_o$$

w = unit wet weight of cable
h = ocean depth
T_o = bottom tension

It is implicitly assumed that T_o may be chosen and monitored by a perfect tensioner on board the ship since tension at the ocean surface Z = 0 is given by $(T_o + wh)$.

7.3.4.2 Cable Angles of Attack

The next task consists in determining the cable geometry between touchdown and attachment point. Ideally, the cable is supposed to be laid on the ocean floor along a path parallel to the ship route as shown in Figure 7.9.

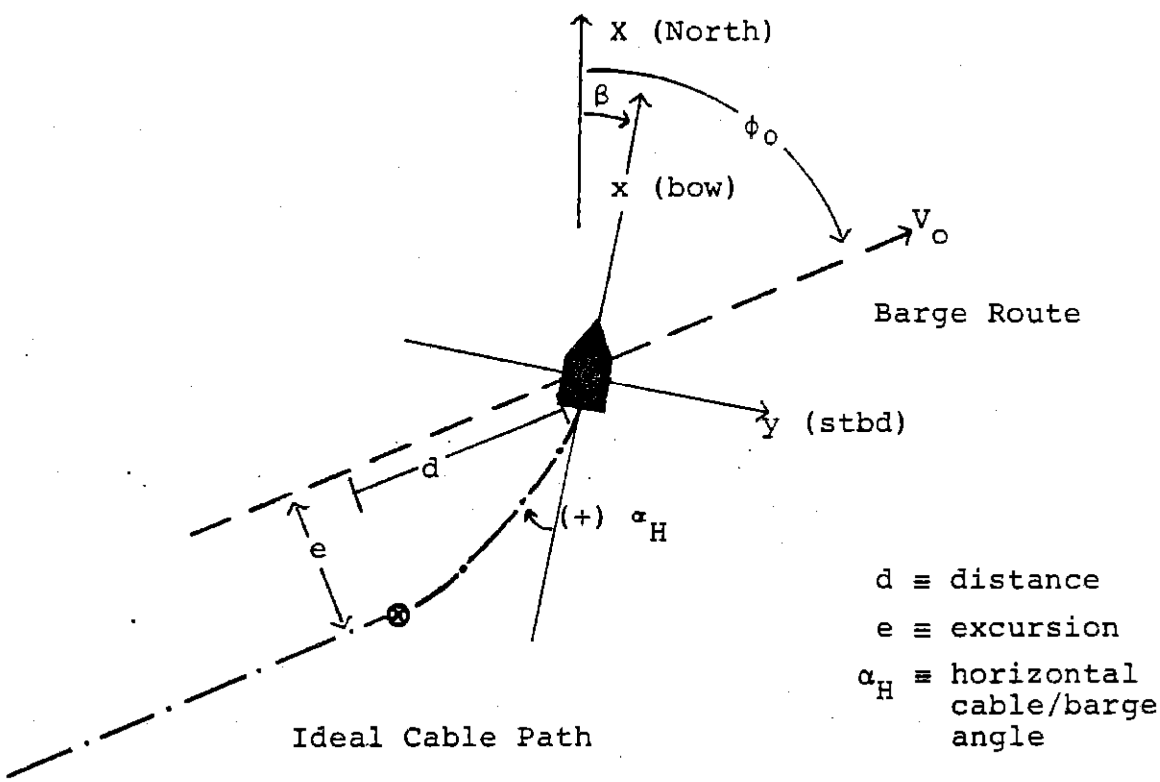


Figure 7.9 Cable and Vessel Path

~~Furthermore, the conventions depicted in Figure 7.10 are chosen~~ to model any three-dimensional current stratification of n layers:

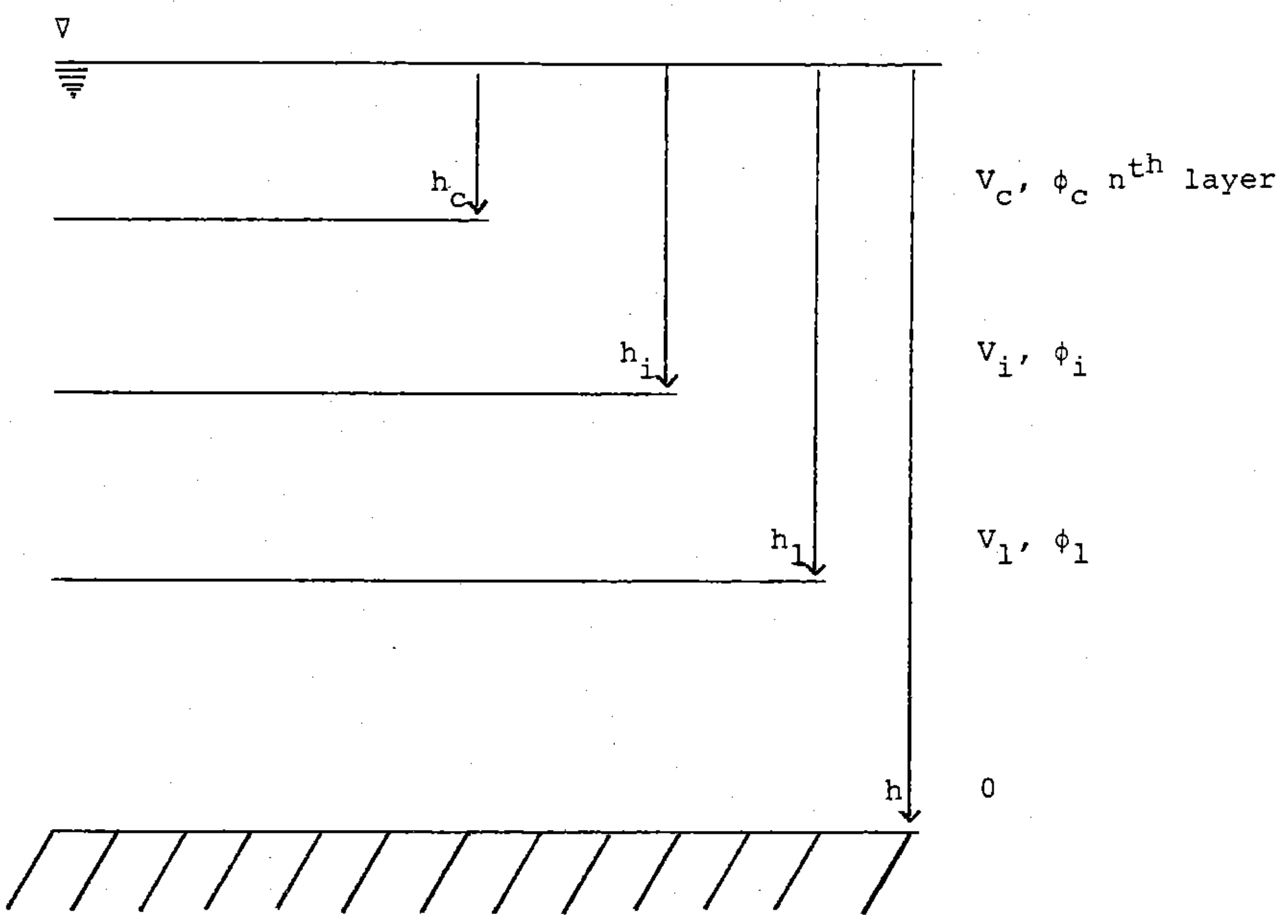


Figure 7.10 Current Stratification

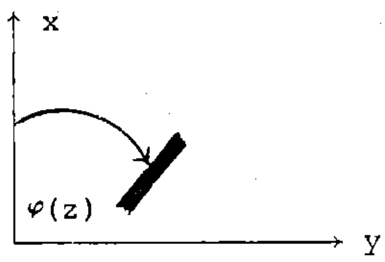
The n^{th} layer corresponds to the surface current. Near the bottom, no current exists and the cable has a catenary shape.

For each layer, the fluid velocity relative to the cable is determined by:

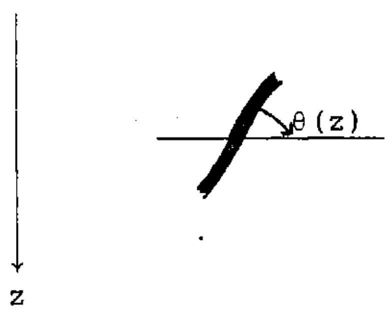
$$V_i^1 = \left\{ (V_o \cos \phi_o + V_i \cos \phi_i)^2 + (V_o \sin \phi_o + V_i \sin \phi_i)^2 \right\}^{\frac{1}{2}}$$

$$\phi_i^1 = \tan^{-1} \left[\frac{V_o \sin \phi_o + V_i \sin \phi_i}{V_o \cos \phi_o + V_i \cos \phi_i} \right]$$

At each depth, the cable configuration is defined by two angles θ and φ:



and in the vertical plane $\varphi = \varphi(z)$



The following equations are integrated by means of a finite-difference scheme:

$$d\theta = \frac{d\eta}{\sin\theta\left(\frac{T_o}{w} + \eta\right)}\left[\cos\theta - \frac{\cos\alpha_i^1}{\sin^2\alpha_i^1}\left(\cos^2\psi\sin^2\theta + \sin^2\psi\right)^{\frac{1}{2}}\cos\psi\sin\theta\right]$$

$$d\psi = \frac{d\eta}{\sin\theta\cos\theta\left(\frac{T_o}{w} + \eta\right)}\left[-\frac{\cos\alpha_i^1}{\sin^2\alpha_i^1}\left(\cos^2\psi\sin^2\theta + \sin^2\psi\right)^{\frac{1}{2}}\sin\psi\right]$$

where, $\eta \equiv h - z$

$\psi \equiv \phi_i^1 - \varphi$; and

the critical angle (α_i^1):

$$\alpha_i^1 = \cos^{-1}\left\{\sqrt{1 + \frac{1}{4}\left(\frac{\varkappa}{V_i^1}\right)^4} - \frac{1}{2}\left(\frac{\varkappa}{V_i^1}\right)^2\right\}$$

$$\varkappa = \left(\frac{2w}{\rho C_D D}\right)^{\frac{1}{2}}$$

C_D = drag coefficient of the cable

D = cable diameter

The integration starts at the touchdown point $\eta = 0$

where, $\varphi = \phi_o$; $\theta = 0$ if $T_o \neq 0$

and,

$\theta = \alpha_c$ if $T_o = 0$

(α_c is the critical angle defined for the pseudocurrent velocity V_o.) It may be seen that special care is needed near the bottom because $\sin\theta\ (\frac{T_o}{w} + \eta)$ vanishes; for this reason, integration is started at a small value $\eta = \varepsilon$ where $\varphi = \phi_o$

$$\theta(\varepsilon) = \tan^{-1}\left\{2\tan\frac{\alpha_c}{2}\left[\frac{\gamma w \varepsilon}{T_o(1+\tan^4 \alpha_c/2)}\right]^{\frac{1}{2}}\right\}$$

where,

$\gamma = 2\csc^2\alpha_c - 1$ if $T_o \neq 0$

$\theta(\varepsilon) \equiv \alpha_c$ for $T_o = 0$

The cable angles of attack, as it is deployed from the vessel, are known when the integration reaches the ocean surface $\eta = h$, yielding the values θ_S and φ_S.

7.3.4.3 Cable Touchdown Point and Suspended Length

Although it is not strictly necessary to know the location of the touchdown point with respect to the barge or what length of cable is suspended, the integration scheme presented above provides such information at no extra effort. Let s, e and d be, respectively, the suspended length, the excursion and the distance as functions of η, with the conventions depicted in Figure 7.11 (also see Figures 7.7 and 7.9).

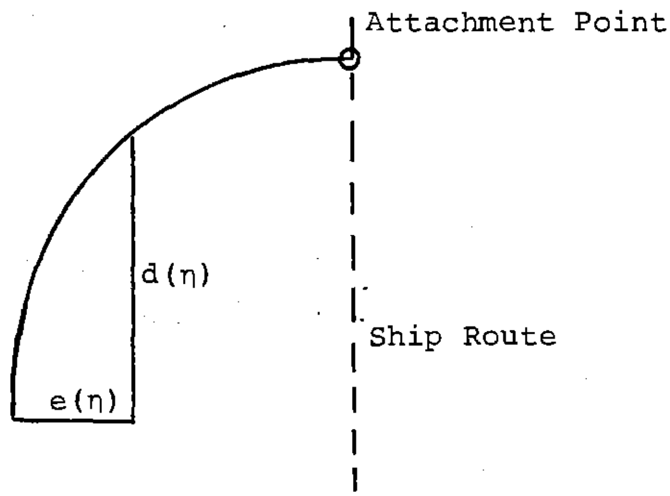


Figure 7.11 Cable Distance and Excursion

The following integration scheme will yield s(h), e(h) and d(h) when completed:

$$ds = \frac{d\eta}{\sin\theta}$$

$$de = \frac{d\eta \cos\theta}{\sin\theta} \sin(\phi_o - \varphi)$$

$$dd = \frac{d\eta \cos\theta}{\sin\theta} \cos(\phi_o - \varphi)$$

with the initial conditions $s(o) = e(o) = d(o) = 0$. Again, the integration must start at a small value $\eta = \varepsilon$ (if $T_o \neq 0$); then:

$$e(\varepsilon) = 0$$

$$S(\varepsilon) = d(\varepsilon) = \left[\frac{T_o\ (1 + \tan^4 \alpha_c/2)\,\varepsilon}{w\gamma}\right]^{\frac{1}{2}} C\tan \alpha_c/2$$

In summary, the task-related loads are modeled as follows:

$$F_{TR_x} = -\ (T_o + wh)\ \cos\ \theta_s\ \cos(\varphi_s - \beta)$$

$$F_{TR_y} = -\ (T_o + wh)\ \cos\ \theta_s\ \sin(\varphi_s - \beta)$$

$$M_{TR} = F_{TR_y} \ell_{cx} - F_{TR_x} \ell_{cy}$$

$$\theta_s = \alpha_v \quad = \text{Vertical Cable/Barge Angle}$$

$$(\varphi_s - \beta) = \alpha_H = \text{Horizontal Cable/Barge Angle}$$

where (l_{cx}, l_{cy}) are the coordinates of the attachment point in the reference frame of the ship.

7.3.5 THRUSTERS

In the foregoing, environmental and task-related loads have been identified and assessed. All these forces and moments must be statically balanced by means of thrusters or tugs (somehow behaving like fixed thrusters). Therefore, we define:

$$F_x = F_{A_x} + F_{C_x} + F_{WD_x} + \Delta F_{WD_x} + F_{TR_x}$$

$$F_y = F_{A_y} + F_{C_y} + F_{WD_y} + \Delta F_{WD_y} + F_{TR_y}$$

$$M = M_A + M_C + M_{WD} + \Delta M_{WD} + M_{TR}$$

There exists basically two ways to statically position the vessel: by means of three fixed thrusters (or tugs), or by resorting to a pair of steerable thrusters.

7.3.5.1 <u>Fixed-Axis Thrusters or Tugs</u>

The nominal fixed-thruster geometry is shown in Figure 7.12; the distances l_1, l_2, l_3 are algebraically defined. Note that from a mathematical standpoint, there is no difference (at this conceptual-design stage) between fixed thrusters and tugs.

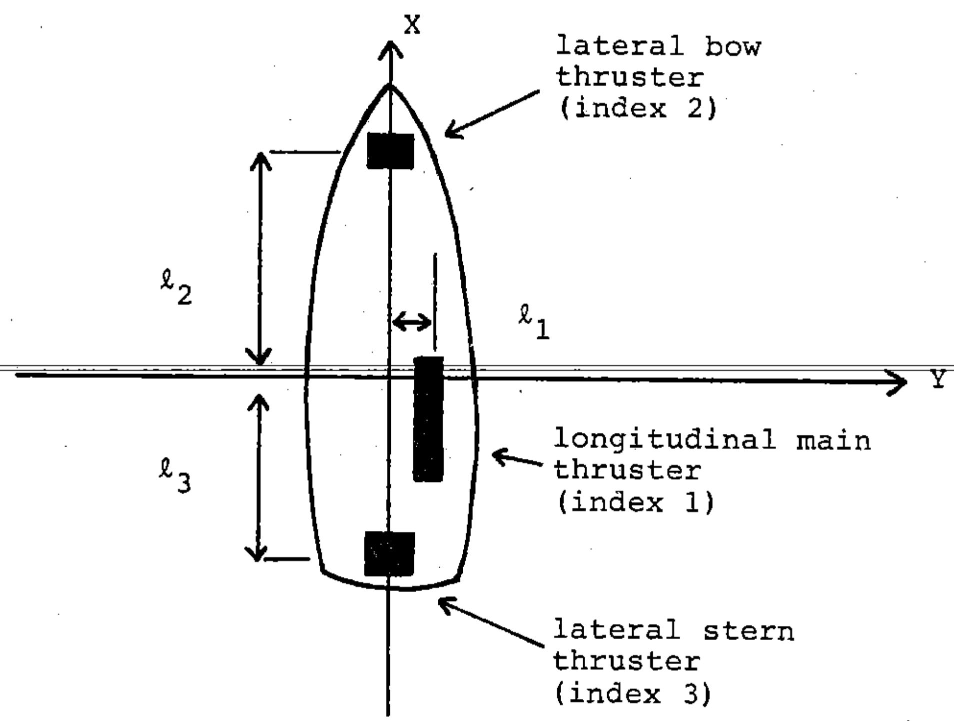


Figure 7.12 Fixed Thrusters Geometry

Letting F_1, F_2 and F_3 be the (algebraic) values of the thrusts respectively applied by the three units, a balance of forces yields the following equations:

$$F_1 = -F_x$$

$$F_2 + F_3 = -F_y$$

$$-l_1F_1 + l_2F_2 - l_3F_3 = -M$$

This linear system can be easily solved:

$$F_1 = -F_x$$

$$F_2 = (-M - l_1 F_x + l_3 F_y)/(l_2 - l_3)$$

$$F_3 = (M + l_1 F_x - l_2 F_y)/(l_2 - l_3)$$

7.3.5.2 Rotatable Thrusters

The nominal steerable-thruster geometry is shown in Figure 7.13; polar coordinates are used so that the distances l_1 and l_2 as well as the thrusts F_1 and F_2 are essentially positive.[1]

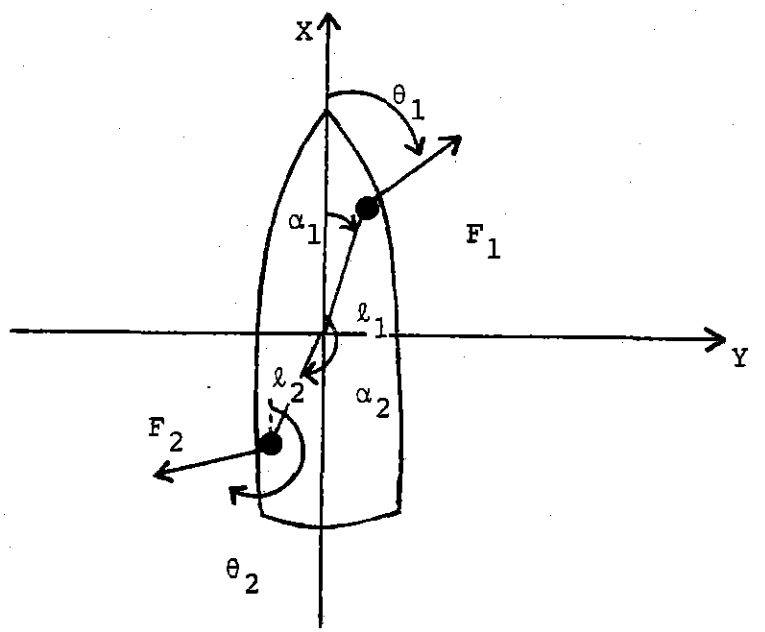


Figure 7.13 Rotatable Thrusters Geometry

The equilibrium equations may be written:

$$F_1 \cos \theta_1 + F_2 \cos \theta_2 = - F_x$$

$$F_2 \sin \theta_1 + F_2 \sin \theta_2 = - F_y$$

$$l_1 F_1 \sin (\theta_1 - \alpha_1) + l_2 F_2 \sin (\theta_2 - \alpha_2) = - M$$

It is seen that there are four unknowns F_1, F_2, θ_1 and θ_2 and only three equations. Consequently, we are going to express F_1, F_2 and θ_2 as functions of θ_1 and give θ_1 any value, thus providing artificially the fourth equation θ_1 = constant. The first two equations yield:

$$F_1 = \frac{- F_x \sin \theta_2 + F_y \cos \theta_2}{\sin (\theta_2 - \theta_1)} \qquad (1)$$

$$F_2 = \frac{F_x \sin \theta_1 - F_y \cos \theta_1}{\sin (\theta_2 - \theta_1)} \qquad (2)$$

Upon substitution of (1) and (2) into the third equation, we obtain, after some straightforward algebra:

$$\theta_2 = \tan^{-1} \left(\frac{B}{A}\right) \qquad (3)$$

$$A \equiv - \ell_1 F_x \sin (\theta_1 - \alpha_1) + \ell_2 F_x \sin \theta_1 \cos \alpha_2 - \ell_2 F_y \cos \theta_1 \cos \alpha_2 + M \cos \theta_1$$

$$B \equiv - \ell_1 F_y \sin (\theta_1 - \alpha_1) + \ell_2 F_x \sin \theta_1 \sin \alpha_2 - \ell_2 F_y \cos \theta_1 \sin \alpha_2 + M \sin \theta_1$$

In principle, (1), (2) and (3) with θ_1 = constant represent a completely determined set of equations. The special case $\theta_1 = \theta_2$, however, must be treated separately; one can easily derive the following:

$$\theta_1 = \tan^{-1}\left(\frac{F_y}{F_x}\right)$$

$$F_1 = \frac{-M + (F_x/\cos\theta_1)\ell_2 \sin(\theta_1 - \alpha_2)}{\ell_1 \sin(\theta_1 - \alpha_1) - \ell_2 \sin(\theta_1 - \alpha_2)}$$

$$F_2 = \left(\frac{F_x}{\cos\theta_1}\right) - F_1$$

If $F_x = 0$ replace $F_x/\cos\theta_1$ by $F_y/\sin\theta_1$

7.3.5.3 Inflow-Current Thrust Degradation

If one wishes to know the thruster commands needed to supply the required thrust as computed above, provision must be made for thrust degradation due to inflow current effects. A very simple linear model is used here adapted from References 7.3 and 7.10:

$$F_i = F_{ic}\,(1 - \varepsilon_i V_i) \qquad i = 1, 2, 3$$

F_i = thrust applied to the barge

F_{ic} = thruster command

ε_i = linear thrust degradation factor; ranging between values of 0.15/m/sec (0.076/knot) and 0.07/m/sec (0.034/knot), depending upon specific configuration.

V_i = inflow current velocity.

For fixed thrusters, we have:

$$V_1 = \frac{F_1}{|F_1|} \left\{ V_c \cos(\phi_c - \beta) + V_o \cos(\phi_o - \beta) \right\}$$

$$V_{2,3} = \frac{F_{2,3}}{|F_{2,3}|} \left\{ V_c \sin(\phi_c - \beta) + V_o \sin(\phi_o - \beta) \right\}$$

For rotatable units, we have:

$$V_{1,2} = \cos(\theta_{1,2} - \alpha_o)\, V_R$$

where α_o and V_R are defined above. The knowledge of the thruster commands is useful when considering the controller design. In a typical PID (proportional-integral-differential) controller, static loads are balanced by the integrator, the gain of which is sized according to F_{ic}, as outlined in Reference 7.3.

7.3.5.4 Cost Function

The goal of the present study is eventually two-fold. It consists in sizing propulsion units properly and also in choosing the best vessel heading β in given operational conditions. Both tasks require the knowledge of the amount of power P that must be supplied. P may be written as:

$$P = K \sum_i F_i$$

where K is a proportionality constant. In the above formula, one should be cautious with the fact that K depends upon the angular velocity (rpm) of the thrusters. As the thrust is degraded due to inflow current effects, the effective angular speed increases such that the power required remains constant within the range of parameters considered in this study (Ref 7.3). At the conceptual design level, we have considered undegraded thrust magnitudes to determine the power required assuming a relationship of 149 N/kW (25 lbs/HP). Thus, it is advised to consider undegraded thrust magnitudes with the optimal value of K. Therefore, the following cost function is defined:

$$C(\beta) = |F_1| + |F_2| + |F_3| \quad \text{, for fixed thrusters or tugs}$$

$$C(\beta, \theta_1) = F_1 + F_2 \text{ ,} \qquad \text{for rotatable thrusters}$$

Our purpose is to determine β_o and C_o such that

$$C_o(\beta_o) = \min_{\beta} (C(\beta)) \text{ ;} \quad \text{or}$$

$$C_o(\beta_o) = \min_{\beta} (\min_{\theta_1} (C(\beta,\theta_1)))$$

Note that minimizing is performed under constraint: there is a limited interval of acceptable values for the cable angles of attack θ_S and φ_S. For instance, Western Gear requires that

$$|\sin (\varphi_S - \beta)| \cos \theta_S < 0.174$$

for their conceptual design of a Cable Handling System.

7.3.6 SUMMARY

The mathematical model of the balance of equilibrium (static) forces and moments on the cable-laying barge by means of devices providing thrust vectors was the basis for the computer model STAT. This analytical tool was utilized to determine thrust vector requirements for a given environmental and operational input. In this fashion the amount of power [directly proportional to undegraded thrust via the proportionality constant 149 n/kW (25 lbs/HP)] required to keep the baseline barge under a prescribed steady course (ϕ_o) was determined as a function of crabbing angle ($\beta - \phi_o$).

Tables 7.9 and 7.10 tabulate the information obtained with STAT for optimal heading. Circled parameters indicate values recommended as upper limits for the different thrust devices under Alenuihaha baseline environment. The family of solutions obtained with Rotatable Thrusters for a given crabbing angle and route is contrasted against Fixed (Tugs) Thrusters in Tables 7.11 and 7.12.

To size the thrust devices for the commercial system, an extreme operational environment was postulated (see Table 7.1). This plausible environment corresponds to colinear winds, current and seas (no swell) of Alenuihaha magnitude flowing towards the barge. The cable angle restrictions imposed by the Cable-Handling-System are such that a beam-colinear extreme environment is not operational. (Note that in Tables 7.9 and 7.10 this restriction is satisfied). The following thrust (power) is required for the baseline barge under the extreme operational (head) environment:

- Rotatable Thrusters

V_o = 1 m/sec (2 knots)

$T_1 = T_2 =$ 325.6 kN (73.2 Kips)

$P_1 = P_2 =$ 2185 kW (2928 HP)

$\theta_1 = \theta_2 = 0°$

V_o = 0.5 m/sec (1 knot)

$T_1 = T_2 =$ 229 kN (51.5 Kips)

$P_1 = P_2 =$ 1537 kW (2060 HP)

$\theta_1 = \theta_2 = 0°$

- Fixed Thrusters or Tugs

V_o = 1 m/sec (2 knots)

T_x = 651 kN (146.4 Kips)

P_x = 4369 kW (5856 HP)

$T_{y_{bow}} = T_{y_{stern}} = 0$

V_o = 0.5 m/sec (1 knot)

T_x = 458 kN (103 Kips)

P_x = 3074 kW(4120 HP)

$T_{y_{bow}} = T_{y_{stern}} = 0$

Assuming a required lay speed (barge forward speed, V_o) of 1 m/sec (2 knots) the following system is optimal to meet requirements imposed by the extreme operational and Alenuihaha baseline environments (see Figure 7.5 for geometry):

- Two Rotatable Thrusters each rated at nominal values of 333.6 kN (75 Kips) corresponding to 2240 kW (3000 HP).

This system can meet all conditions summarized in Tables 7.9 through 7.12. Note that in these tables $\alpha_V = \theta_S$ and $\alpha_H = (\varphi_S - \beta)$.

Fixed thrusters (tugs) will require an axial unit rated at 4400 kW (5900 HP) to meet the extreme operational environment, in addition to the two lateral units rated at nominal values of 1490 kW (2000 HP) each.

The list of input parameters for the equilibrium or quasistatic model described in this section is as follows:

List of Input Parameters for Quasistatic Model

Environment

V_A/ϕ_A = wind velocity and angle (measured clockwise from North

V_C/ϕ_C = surface current velocity and angle

n = number of current layers

V_i/ϕ_i = deep current velocity and angle ($i = 1, 2, \ldots,$ $n - 1$)

h_i = depth of i^{th} layer ($i = 1, 2, \ldots, n$)

h = total water depth

ρ = seawater density

g = gravity constant

H_S = wave-spectrum significant wave height

ω_o = circular frequency of wave spectral peak

γ = wave-spectrum angle

$H_{SW}/\omega_{SW}/\gamma_{SW}$ = swell height, frequency and direction

ρ_A = air density

Vessel

β = heading

V_o/ϕ_o = ship velocity and angle of ship route

$C_{AX}/C_{AY}/C_{AZ}$ = wind-drag coefficients (defined with respect to ship access)

$C_R/C_F/C_{cy}/C_{cz}$ = current-drag coefficients

B = beam

L = length

T = draught

C_B = block coefficient

H = height (including superstructures)

Cable

T_o = bottom tension

w = unit wet weight

l_{cx}/l_{cy} = coordinates of attachment joint from coordinate system center

D = diameter

C_D = drag coefficient

Thrusters

- fixed-axis units:

  ε_i = inflow current thrust degradation factor (i = 1, 2, 3)

  l_i = distance from thrusters axis to ship axis (i = 1, x axis; i = 2, 3, y axis)

- steerable units:

  l_i/α_i = polar coordinates of thruster locations (i = 1, 2)

TABLE 7.9

RANGE OF SOLUTIONS FOR SOUTHEAST ROUTE ACROSS THE ALENUIHAHA, FROM MAUI TO HAWAII

(7000 ft Water Depth; 10,000 lb Bottom Tension; Baseline Cable and Barge; ϕ_o = 135°)

	Barge Heading Angle β (°T)	Crabbing Angle $\beta-\phi_o$ (°)	Loads on Barge due to Cable, Wind, Sea, Swell and Current F_x (Kips)	F_y (Kips)	M_z (Kips-ft)	Rotatable-Thrusters Minimum Cost Solution T_1 (Kips)	θ_1 (°)	T_2 (Kips)	θ_2 (°)	Fixed Thrusters T_x (Kips)	$T_{y_{bow}}$ (Kips)	$T_{y_{stern}}$ (Kips)	Horizontal Cable/Barge Angle (α_H) (°)
V_o = 2 knts	150	15	-61.7	-9.2	-93	32	8	30.4	8	61.7	4.8	4.4	22
α_V = 66°	165	30	-64.7	32.2	-3,474	2.1	333	70.1	334	64.7	-7.0	-25.2	7
Excursion = 1254 ft	180	45	-61.7	66.4	-5,614	19.5	313	71.2	313	61.7	-18.4	-48	-8
Distance = 3241 ft	195	60	-52	92.6	-6,603	37.8	299	70.1	299	52	-28.9	-63.7	-23
V_o = 1 knot	145	10	-32.1	-21.8	2,764	8.4	34	30.4	34	32.1	3.6	18.2	42
α_V = 75°	160	25	-36.0	4.2	-785	14.5	3	22.1	347	36.0	0	-4.2	27
Excursion = 917 ft	175	40	-37.6	25.0	-3,417	2	13	43.5	325	37.6	-3.5	-21.5	12
	180	45	-37.0	30.6	-4,026	1.4	320	46.6	320	37.0	-4.7	-25.9	7
Distance = 2168 ft	225	90	-13.2	65.6	-4,072	21.3	281	45.6	281	13.2	-22.1	-43.5	-38

TABLE 7.10

RANGE OF SOLUTIONS FOR NORTHWEST ROUTE ACROSS THE ALENUIHAHA, FROM HAWAII TO MAUI

(7000 ft Water Depth; 10,000 lb Bottom Tension; Baseline Cable and Barge; $\phi_o = 315^\circ$)

	Barge Heading Angle β (°T)	Crabbing Angle $\beta-\phi_o$ (°)	Loads on Barge due to Cable, Wind, Sea, Swell and Current: F_x (Kips)	F_y (Kips)	M_z (Kips-ft)	Rotatable-Thrusters Minimum Cost Solution: T_1 (Kips)	θ_1 (°)	T_2 (Kips)	θ_2 (°)	Fixed Thrusters: T_x (Kips)	$T_{y_{bow}}$ (Kips)	$T_{y_{stern}}$ (Kips)	Horizontal Cable/Barge Angle (α_H) (°)
V_o = 2 knts	260	-55	-51.8	-38.5	5,811	10.1	37	54.5	37	51.8	4	34.5	21
α_V = 63°	275	-40	-58.7	2.0	5,827	26.6	323	40	21	58.7	-16.3	14.3	6
Excursion = -1334 ft	290	-25	-61.8	36.9	4,565	71.6	329	0.3	329	61.8	-30.4	-6.5	-9
Distance = 3545 ft	300	-15	-61.3	57.1	2,795	56.2	317	27.6	317	61.3	-35.9	-21.2	-19
V_o = 1 knot	235	-80	-20.7	-41.1	2,578	15.5	63	30.5	63	20.7	13.8	27.3	33
α_V = 73°	250	-65	-24.9	-13.4	3,677	2.4	313	27.8	33	24.9	-3	16.4	18
Excursion = -980 ft	265	-50	-28.3	15.2	4,356	28.5	313	10.5	32	28.3	-19.1	3.9	3
Distance = 2351 ft	280	-35	-30.5	35.4	3,971	40.7	311	5.9	311	30.5	-28.1	-7.3	-12
	300	-15	-30.4	50.8	1,225	34.1	301	25.1	301	30.4	-28.6	-22.2	-32

Table 7.11

SOUTHEAST ROUTE CRABBING ANGLE 30°

Barge Loading and Cable Geometry for Crabbing Angle 30°

F_x = - 64.7 Kips
F_y = - 32.2 Kips
M_z = - 3,474 Kips ft
V_o = 2 knots

α_H = 7°
α_V = 66°
Excursion = 1254 ft
Distance = 3241 ft
Suspended Length= 7989 ft

Rotatable Thrusters

- Maximum Thrust Available per Thruster: 75 Kips (3000 HP each)
- Geometry as Given in Text
- Solutions for Crabbing Angle = 30°

T_1 (Kips)	θ_1 (°)	T_2 (Kips)	θ_2 (°)
2.8	183	74.7	335
1.6	193	73.5	334
1.1	203	73	334
0.9	213	72.7	334
0.8	223	72.5	334
0.7 to 1.4	233 to 323	72.4 to 71	334
2.1	333	70.1	334

Fixed Thrusters

- Thrusters Geometry as Given in Text
- Solution for Crabbing Angle = 30°

T_x (Kips)	$T_{y_{bow}}$ (Kips)	$T_{y_{sterm}}$ (Kips)
64.7	-7	-25.2

Table 7.12

NORTHWEST ROUTE CRABBING ANGLE -25°

Barge Loading and Cable Geometry for Crabbing Angle -25°

F_x = -61.8 Kips		α_H	= -9°
F_y = 36.9 Kips		α_V	= 63°
M_z = 4,565 Kips ft		Excursion	= - 1334 ft
V_o = 2 knts		Distance	= 3545 ft
		Suspended Length	= 8118 ft

Rotatable Thrusters

- Maximum Thrust Available per Thruster: 75 Kips (3000 HP each)
- Thruster Geometry as Given in Text
- Solutions for Crabbing Angle = -25°

T_1 (Kips)	θ_1 (°)	T_2 (Kips)	θ_2 (°)	
26.6	243	75	350	
25.7	253	70.4	350	
25.5	263	65.9	350	
26.1	273	61.4	350	
27.7	283	56.4	350	
30.4	293	50.7	350	
34.8	303	43.5	350	{ Balanced Solutions
42.3	313	33.4	350	
56.1	323	17.2	350	
71.6	329	0.3	329	{ Minimum Cost

Fixed Thrusters

- Thruster Geometry as Given in Text
- Solution for Crabbing Agnle = -25°

T_x (Kips)	$T_{Y_{bow}}$ (Kips)	$T_{Y_{stern}}$ (Kips)
61.8	- 30.4	- 6.5

CHAPTER 8

CABLE POSITION AND VESSEL CONTROL

Bottom cable positioning within the appropriate tolerances is one of the major objectives of the integrated control system. Cable position is determined by vessel position and both are discussed in this chapter. Three levels of bottom cable tolerance are considered together with flow diagrams and contingencies.

8.1 VESSEL CONTROL OBJECTIVES

The thrusters on the vessel are used to control three vessel parameters: vessel heading (the direction in which the vessel is pointing), vessel course (the line along which the vessel is moving), and vessel speed.

8.2 VESSEL COURSE

Without any cable offsetting effects, the cable will follow directly behind the surface of the cable laying vessel. In this case, the vessel course and the cable path are identical. Currents, however, can deflect the cable to the right or left of the vessel path as has been shown in Figure 3.5. At 2000 m, the depth of the Alenuihaha Channel, maximum cross currents could deflect the cable 400m. These maximum currents are an exception, normal deflection would be considerably less, particularly when considering there is a square relationship between current magnitude and cable offset

Figure 8.1 illustrates graphically the relation between vessel positional tolerance, current offset and the resultant cable placement accuracy. The diagram also shows three levels of cable placement tolerance. The first level at ± 500m does not require monitoring cable deflection. Even the maximum cable deflection is acceptable under this wide tolerance level. Such tolerance levels would be applicable over smooth bottoms well clear of any obstructions, and where there is adequate area to lay all four cables. The second level of cable tolerance at ± 200m requires some feedback relative to cable displacement. Methods of monitoring the cable location after it has left the vessel is discussed in Chapter 5. Cable deflection measurement under these conditions can be obtained with a combination of top cable angle plus periodic measurements with transponders tied to the lowered cable.

The third level of cable placement accuracy actually involves a completely different mode of cable laying operation. In this case, immediate feedback is required but with underwater systems such as a remote operated vehicle (ROV). The ROV would visually

CABLE PLACEMENT TOLERANCE VS SHIP POSITION AND CURRENT DEFLECTION

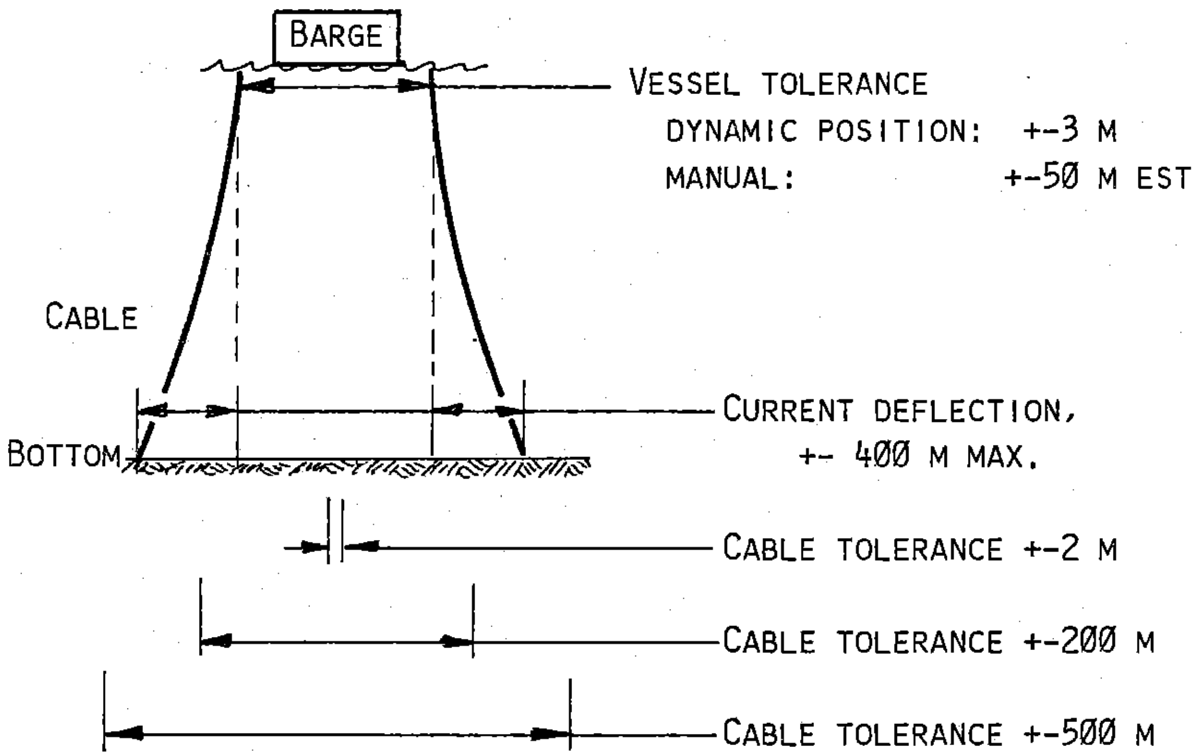


FIGURE 8.1

observe the placement of the underwater cable and provide guidance to the surface vessel. The ROV's visual observation would be relative to a wire rope which had been prelaid and presurveyed for path acceptability. The ROV on the bottom would provide a video signal showing that the actual cable is being laid to the right or left of the desired path. The desired vessel course would then be corrected appropriately on the surface; the vessel course is maintained and relative to the navigational system. This type of operation has been done by Pirelli in the Mediterranean for 200 m of water depth maximum under low currents, not in 2000 m. If required for the commercial system in deep water, this represents a major advancement in the state of the art and is a formidable obstacle in deploying the cable. The major problems relative to performing such an operation are as follows:

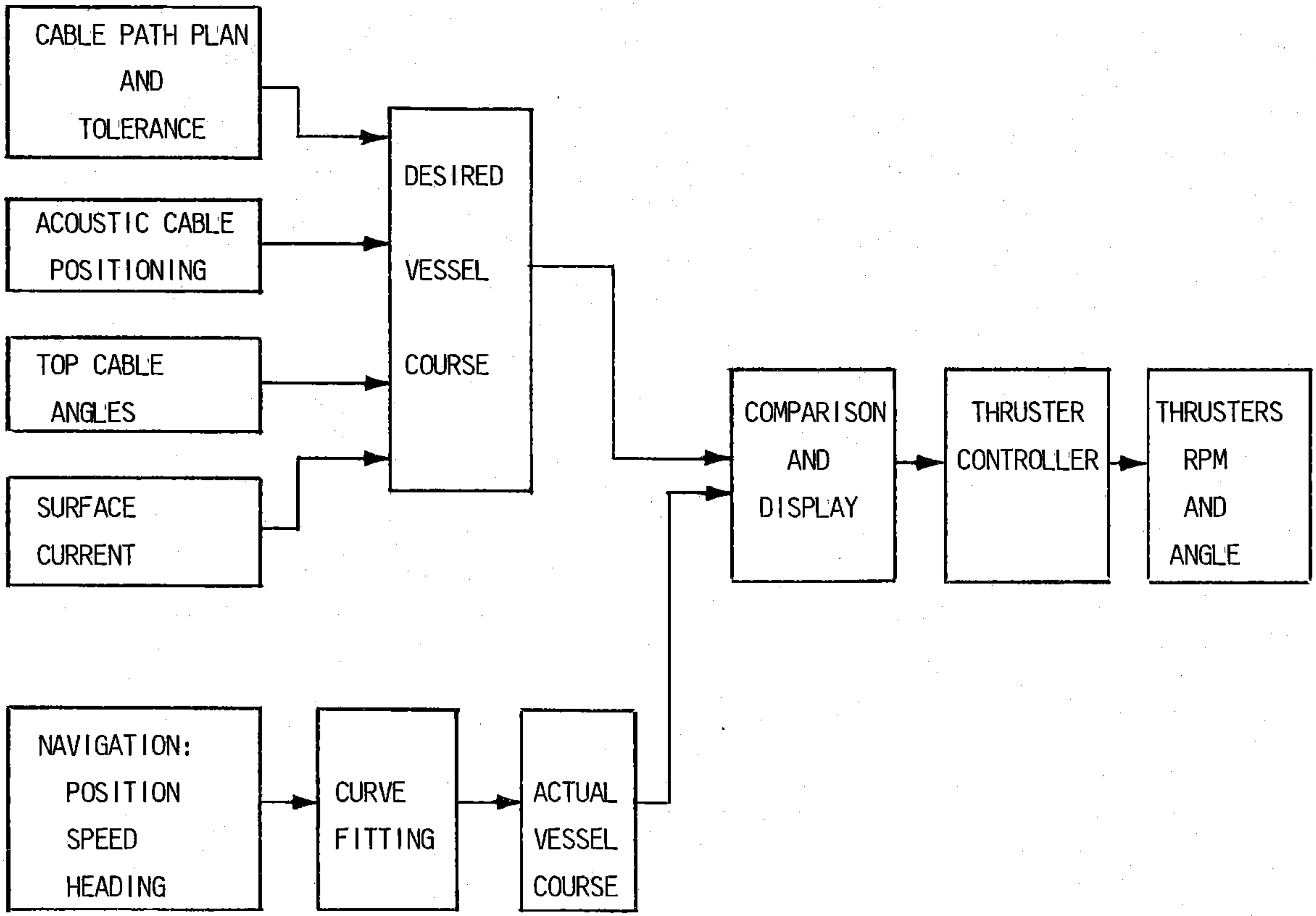
- Precise location of the surface vessel
- Continually operating an ROV on the bottom
- The variability of ocean currents
- The irregularity (radius of curvature) required in the cable path
- The slow cable laying and resultant large weather windows.

Vessel positioning and ROV deepwater operations are within the state of the art and can presently be achieved. The primary concerns are with the two major unknowns: current variability and cable path radius of curvature. With the long length of cable subjected to unsteady currents, the surface vessel may not be able to compensate appropriately. In addition, if the bottom path is highly irregular requiring small radii of curvature, the surface vessel would be required to undergo very large excursions and the cable bottom tensions would have to be very low.

It should be kept in mind that, at present, the need for such precise bottom location, particularly in deep water, has not been determined; it is entirely possible that such an operation is not required in the commercial cable lay. On the other hand, it has also not been determined that such an operation is not required. the HDWC program should keep in mind the potential difficulty of precise cable laying in deep water and efforts should be made to conduct further bottom surveys and determine whether it is a viable concern. If it is a problem, further work is required and it should be included into the HDWC demonstration program.

Figure 8.2 is a block diagram illustrating the vessel course control. The desired vessel course is computed on the basis of a cable path plan and current corrections made on the basis of ROV observation, acoustic markers and/or top cable angles (Chapter 5). At the same time, the navigational system provides position and speed of the vessel from which the actual ship course is computed. A comparison of the desired course relative to the actual course is made and all the information displayed. (Figure 8.3). The displayed and/or digital information is provided to the

FIGURE 8.2 VESSEL COURSE CONTROL



thruster controller which can either be a human operator on a joystick or a fully automated dynamic positioning system. Discussions on manual versus automatic controllers are given in Section 8.5.

8.3 VESSEL SPEED

Maximum vessel speed is primarily at the option of the captain. He is primarily limited by the cable handling subsystem maximum speed of 1 m/s (2 kts) and maximum thruster power. It is possible that the captain could drive the vessel faster than the cable handling equipment could pay out the cable and an interfacing alarm is required from the CHSS equipment to the captain and vessel thruster operator. In particular, it should be noted that while going down underwater slopes, the cable speed exceeds the vessel speed and, under these conditions, the vessel must be slower than 1 m/s (2 kts).

8.4 VESSEL HEADING

Vessel heading is primarily determined on the basis of Figure 3.1 which illustrates heading restrictions as a function of the cable angular deflection at the overboarding sheave. A relatively straightforward computation can be made based on cable angle measurements which results in a vessel heading window which is acceptable for proper cable handling. This window along with the actual vessel heading should be graphically displayed on the CRT which also shows vessel position and vessel course. A typical display showing pertinent information is shown in Figure 8.3.

The vessel captain can, at his discretion, select any vessel heading within the acceptable heading window. The primary considerations in his selection would be surface currents and waves. Broadside currents place the largest loads on the vessel and these loads can be lowered by changing the vessel heading. In addition, various vessel orientations relative to the waves can reduce vessel motions at the stern and therefore reduce dynamic cable tensions. This latter consideration would be particularly important when the cable handling subsystem is not functional.

8.5 AUTOMATIC VS MANUAL CONTROL

The actual commands to the two rotatable thrusters can be either manual or automatic. The thruster manufacturer can provide a single joystick control such that the operator can vary forward thrust, lateral thrust and turning moment. With such a joystick control and by viewing a CRT similar to that shown in Figure 8.3, an operator could fairly easily move the vessel along a desired course, depending upon the acceptable tolerance on that course. Based on conversations with Sumitomo, manual control cable vessel accuracy is nominally ±50 m. For most cable laying operations, such a tolerance is acceptable.

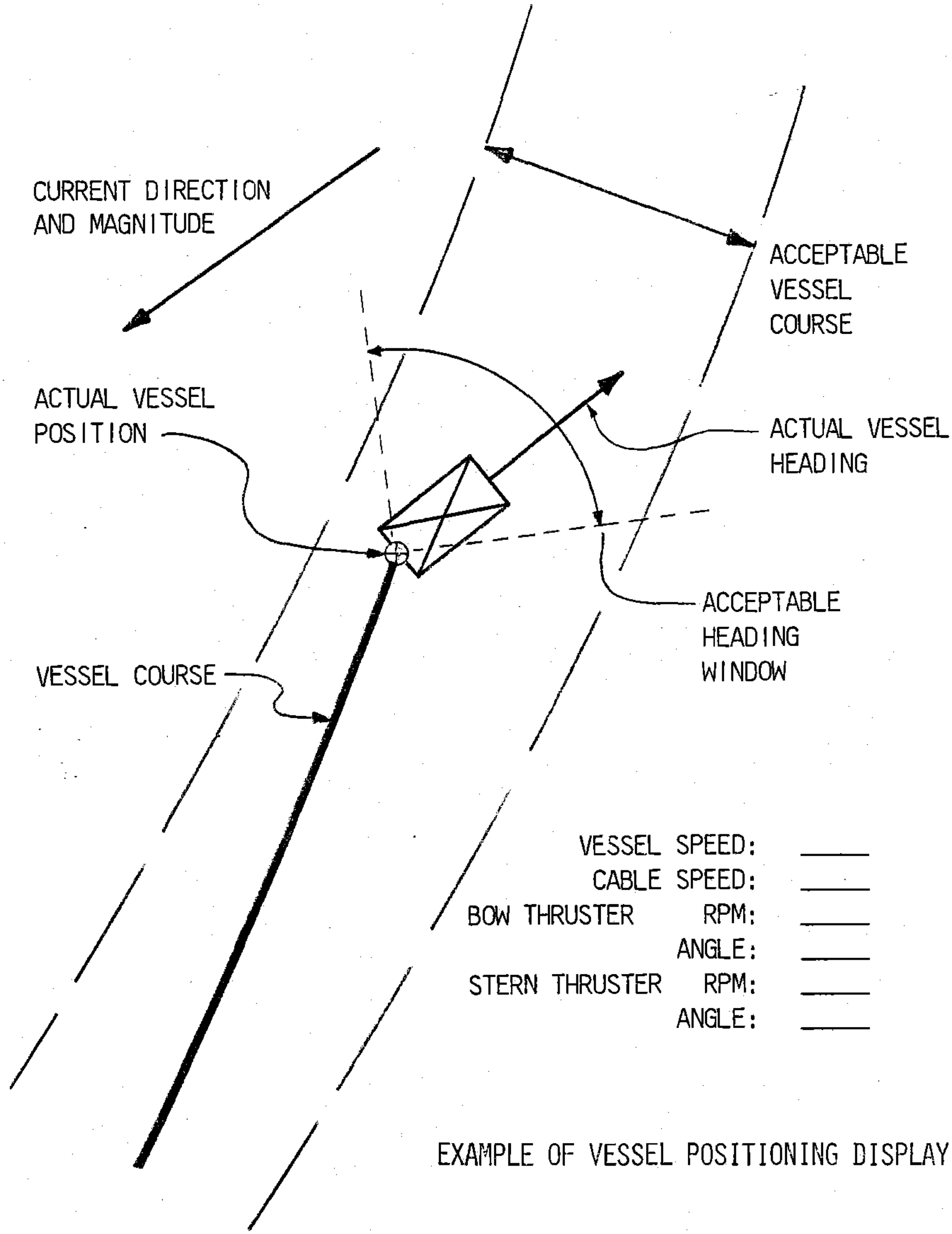


FIGURE 8.3 CRT DISPLAY FOR VESSEL CONTROL

In the case of precisely laying the cable on the bottom, (tolerance level 3, ±2m) the cable laying is a slow, tedious and very precise process. The human operator would not be able to give the precision required. There are commercially available dynamic positioning systems which can maintain the vessel along the course within ± 3 m, within the accuracy of the navigational system. Typical of such a dynamic positioning system would be the Honeywell ASK3000. It receives as input data from the navigational systems, vessel heading and an optional wind sensor for wind forced compensation. Its color display graphics shows the status of all sensors plus a plot of the vessel on course. The cost for a single system is between $400,000 and $500,000 and the costs for a system with full redundancy is between $700,000 and $1,100,000. When operating in response to video signals coming from an underwater ROV, the human operator would input course corrections (example: shift the course to the right 2 m) and the dynamic positioning system would follow the new course.

There are significant differences between the manual control systems and the dynamic positioning system in terms of cost and operation under contingency situations. By normally operating under manual control, the crew will become well trained in handling the vessel and can more easily respond under emergency situations. The dynamic positioning system can be justified only if it is superior in terms of cost or its more precise positioning capability is a mandatory requirement for the cable operation. In terms of cost, the dynamic positioning system cannot be justified. Skilled human operators will have to be present, no matter if they are manning the controls or not. In terms of the superior positioning capability of the automatic system, it is only necessary in the case of precisely laying the cable along the bottom and the need for such precise laying has not yet been determined. At this time, manual control is recommended with the understanding that if precise bottom cable positioning is required, dynamic positioning systems will be required.

8.6 CONTINGENCIES

The most serious contingency situation which could occur is the loss of one or more thrusters. The propulsion systems are normally highly reliable and such an event is unlikely. Loss of one thruster would eliminate the possibility of vessel rotation. With the remaining thruster the captain can only hope to pull against the cable keeping the vessel in line with the cable and hopefully near the cable path such that the cable is not dragged over the bottom and bottom tension maintained. Tug assistance would be required. Under severe weather conditions and without the possibility of immediate thruster repair, the captain would probably be forced to drop the cable.

The navigation system is the second most critical item in cable and vessel positioning. Redundancy in the navigation system is mandatory with two fully operating receivers on the vessel and two transmitters at each shore station. If any one unit goes out, it should be immediately replaced such that a backup system is always available.

Redundant systems are also recommended for the controller which calculates vessel course corrections based on calculations of cable position. If this information is lost, however, the vessel can proceed on the basis of the navigation system alone and maintaining the status quo relative to a fixed offset between cable path and vessel course. In the case of precise cable positioning, the loss of the controller would necessitate stopping the cable lay and maintaining position until the controller could be repaired. Online backup systems are recommended.

There is some interaction between the cable handling subsystem and the vessel controller. In the case of CHSS failures, the cable vessel needs to come to a complete stop and positioning itself along the cable path with a heading that minimizes cable dynamics and facilitates CHSS repair.

CHAPTER 9

CONTROLLER

The term controller is used in this report for the hardware and equipment that performs the computations to determine the cable geometry, the vessel course, and the cable tension. The controller is shown in Figure 1.1, the Block Diagram of the Control System, as the system within the dashed box. The controller takes information from the sensors, does computations to determine critical parameters, displays all information, makes a decision on what action is to be taken and outputs the appropriate commands to the vessel position and cable control systems.

This chapter discusses what is required of the controller and how these requirements can be fulfilled. The requirements discussed include the interfacing of the controller with equipment discussed in previous chapters, the interfacing with man, the degree of automation required in the controller, the degree of redundancy for reliability, and a list of types of equipment that could be used. Much of the discussion assumes a computerized controller, but this need not be so. Any part of, or all of, the controller could be human.

9.1 CONTROLLER TASKS

The controller is essentially the accountant of the operation of the cable laying vessel. It has available to it all the information on both the planned lay, and the actual lay as it happens. With this information it performs some calculations to determine actual positions and tension of the cable on the bottom. From the actual position and tension it determines what actions are required and issues commands to carry out these actions.

The first task in the controller's cycle is to interrogate the sensors. The interrogation will provide the controller with a great deal of input information as shown in Table 9.1. The interrogation is discussed further in section 9.4.

For the second task in its cycle, the controller will have to carry out several computations. The computations include:

- The cable geometry, from the cable angles, tensions, lengths, navigation, bathymetry and surface currents (see Figure 4.2).
- The top cable tension, from the geometry of the cable.
- The new vessel course, as desired to maintain the cable on the planned path.

The frequency of these calculations is a function of tolerance. Using a tolerance of ± 2000 kg (4500 lbs) in cable tension gives approximately a ± 70 m (230 ft) error in cable

TABLE 9.1

TABLE OF CONTROLLER INPUTS

DATA	SIZE Chrs.	FREQ. RANGE	REMARKS
Navigation			
X	8	20/min.	
Y	8	20/min.	
Velocity	5	20/min.	
Error circle	6	20/min.	
Vessel Heading	6	3/min.	Gyro compass
Plan			Plan Computer
Cable X	8	1/min.	
Cable Y	8	1/min.	
Depth	6	1/min.	
Cable Data			
Length	8	20/min.	Meter wheel
Angles	10	1/min.	Angle measurement
Tension	6	1/min.	CHSS
Cable Location			Acoustic marker
X	8	3/hr.	Frequency varies
Y	8	3/hr.	with conditions
Depth	8	3/hr.	
Alarms - Faults			
Thrusters	1	-	
CHSS	3	20/min.	
Operators			
Corrections	50	3/hr.	
Manual override	50	-	Informing controller
Alarms	50	-	Informing controller
Environment			
Surface Current			
Velocity	5	1/min.	Averaged
Direction	5	1/min.	Averaged

position or cable length. To get this much error would require the vessel's speed to change 1 m/s (2 Kts) instantaneously while the controller took no action for 70 seconds. As the vessel can't accelerate instantaneously, the sample can be less frequent than 70 seconds. To be on the safe side, take 60 seconds as the period required for cable geometry calculation (see Figure 4.2).

The sampling frequency to maintain the cable position on the planned cable course is a function of the tolerance across the cable path. For the greater tolerances of 500 m (1600 ft) and 200 m (650 ft), the difference between the vessel position and the cable position need only be corrected infrequently, say once per 20 minutes for conditions such as currents. Changes in cable angle give a good indication of any current changes. For the narrow tolerance of 2 m (6.5 ft) the planned vessel course would be continually adjusted manually from ROV observation. The corrections are to the planned vessel course, not to the vessel position. The positioning system gets updates directly from the navigation systems to maintain vessel on the desired course.

The frequency of the computations is therefore driven by the requirement for cable bottom tension of every 60 seconds. This frequency then drives the frequency of input data to the same sampling rate of once every 60 seconds.

The controller's third task is to provide an interface with the operator to both provide data and take commands. All data, both raw and calculated, will be continuously available to the operator upon request. Critical parameters are displayed in readily interpretable form, such as graphs and plots, during normal operation. If any of the parameters vary by more than their expected range or other alarm conditions occur, the controller will immediately notify the operator. The controller will also accept commands from the operator, providing a manual override. In addition, manual overrides should be provided at the propulsion and cable handling subsystem in case of controller failure.

The fourth task for the controller is to interface with and command both the CHSS and the propulsion systems. To the CHSS it will output the cable tension it has determined appropriate. To the vessel control it will output the desired vessel course and vessel heading restrictions.

The final task for the controller is to interface with the data acquisition system (DAS). The DAS is to record descriptive data and parameters for use either after an interruption in the cable laying or for post-lay analysis. The DAS will record the information on a non-volatile media to prevent loss due to power outages or other errors. The interface of the controller to the DAS should be such that during a controller failure the DAS is able to continue recording information from the sensors. The data gathered will be especially useful during the HDWC program for later analysis. For the commercial operation it would provide a final cable position on the bottom.

9.2 AVAILABILITY OF SOFTWARE

Solving the cable geometry and the cable tension do not involve sophisticated programs. Software for similar problems has been developed in the laying of other cables and determining the position of towed 'fish' during surveying. The Hawaii Deep Water Cable is unique in several aspects, already discussed, so custom software is required.

The problem of determining a course and vessel heading has been solved previously in other cable and pipe lays. As discussed in previous chapters, this problem compares present cable position with planned cable position and determines what change in vessel position is needed. As this change is a function of both the cable, the laying conditions and the cable laying equipment, again the problem is a unique one and custom software is required.

Software will also be required for the interface between the controller and the input sensors, CHSS, operators, and DAS. While much communications software exists, large modifications would be necessary to fit it into this system. The more efficient solution is to use existing algorithms to, again, develop custom software.

9.3 CONTROLLER TYPE AND SIZE

This section is to determine what functional capacities are needed to perform the tasks discussed in Section 9.2. These tasks include:

1 Interface with and read all sensors.
2. Perform computations.
3 Interface with operator .
4. Interface with and command the CHSS and propulsion system.
5. Interface with the Data Acquisition System.

This section is organized by the functional requirements on the controller. The section proceeds from the inputs requirements to the computational requirements and finally, to the output requirements.

In Table 9.1 input information to the controller from various sensors is shown. In the table, each data element is shown with its approximate size and required sampling frequency, discussed in section 9.2.

The input information to the controller is assumed to be accurate to the tolerance needed. This accuracy will be achieved by the individual instruments performing a number of samplings and computing a best-fit average. As discussed in previous chapters, this is available on some systems such as the navigation, but would have to be developed in some systems such as cable angle and tensions.

There are two common types of communication interfaces between the sensors and the computer's controller. They are RS232, commonly used in computer communication and IEEE488, a standard used in built-up computing systems. With allowances for communications overhead and extra data in the blocks transmitted by packaged sensor systems, the input is less than 4000 ASCII characters per minute. Using RS232 communications at high baud rates (9600 baud) the 4000 characters would take approximately 10 seconds. Ten seconds is a small fraction of the 60 second cycle period for the controller and is acceptable.

The controller will also have to accept input from the operator. As this is a very disruptive function, it is planned that the operator would interface with a separate microprocessor which would then communicate with the controller. This communications interface would again be RS232 and is included in the 4000 characters above.

The computations that the controller will perform are shown in Table 9.2. While the computations are not complex, iterations may be required. The number of iterations will be small since the solution is solved every 60 seconds and changes are small. A high speed microprocessor, as can be found in advanced desk top computers, can handle these computations in less than 20 seconds.

The controller outputs are shown in Table 9.3. The primary outputs of tension to the CHSS and course to the vessel positioning system will not occupy much communications time. The other outputs of display information for the operator and the record of action for the DAS will require greater quantities of information on the order of twice the input information. The output communication is expected to take on the order of 6 seconds.

The display to the operator will be handled by a separate microprocessor, the same one handling operator input. This operator's computer would store all current information in memory for displaying at the operator's request. The operator's computer will have the time and capacity to show data in graphs and plots with flags alerting the operator to alarms. The reason for having a separate computer for the operator is to avoid interrupting the critical cycle of the controller with the time consuming task of changing displays. A desktop computer, with graphics, will handle this task.

The DAS would be another separate computer, making a record of the action on non-volatile media such as disks or bubble memory. Having the DAS as a separate computer allows for the continued

Table 9.2

CONTROLLER COMPUTATIONS

Cable Geometry	from vessel position, cable length, cable angle and cable tension
Cable Tension	from cable length updates applied to cable geometry solutions
Proper Vessel course	from planned cable path and environmental conditions.

Table 9.3

CONTROLLER OUTPUT

OUTPUT	TO	SIZE Characters	FREQUENCY
Cable Tension	CHSS	6	3/min.
Vessel Course			
Course	Positioning system	12	1/min.
Vessel Heading	Positioning system	12	1/min.
Speed limit (CHSS)	Positioning system	6	1/min.
Tolerances	Positioning system	12	1/min.
Record of Parameters	DAS	1400	3/min.
Display Information	Operators	1400	3/min.

recording of data in the event the controller fails and frees the controller from the task of working with a mass storage media .

The equipment to fulfill the above requirements is all available off the shelf. The main component of the controller would be a high-speed microprocessor capable of communicating through several serial ports. Besides the main controller computer, two computers capable of graphics are needed for interfacing with the operators. Another computer is needed for the DAS to handle the recording and retrieval of information in a fail-safe technique. The biggest difficulty in assembling the hardware is likely to be selecting among the several combinations available.

9.4 INTERFACE WITH MAN

Man is a pivotal component in the controller system. The operator is the final fail safe, he is certainly the most adaptable one available. The automation of the control system is to optimize man's abilities, to take away the thoughtless tasks, and give him the time to concentrate on the critical operations. The operator can provide an excellent interface between the inputs and the outputs of the system and able to exercise judgement on what actions should be taken in contingency situations.

To utilize the operators judgement, all information that the controller processes and uses will always be available in both displays and paper copies. The operators will all be fully trained with knowledge of the algorithms of the operation such that they can detect gross faults.

Transferring information to the operator through computer displays has many advantages. One CRT can be used for many displays, changed at the operator's request. Data from several sources can be displayed on the same CRT at the same time. Information can also be shown in graphical representation for easier understanding by the operator. The CRT displays are adaptable, able to give whatever accuracy is desired as well as displaying calculated parameters. The computer can flag parameters to bring alarm items to the operators attention.

With the automated controller a single keyboard or a joystick can control several separate systems or units. By issuing a single command from the keyboard, the operator may cause dozens of equivalent switches and wheels to be changed in an order predetermined to be optimal. With joystick control of the propulsion system the operator can concentrate on where he wants the vessel to go and let the computer determine the combination of thrusts and directions for the thrusters. Joy stick control is commonly provided with rotatable thrusters as discussed in chapter 8.

9.5 DEGREE OF AUTOMATION

Automation can be justified either due to technical requirements or cost savings. The technical reasons why the controller should be at least partially automated are:

- The number of sensors that must be interrogated and included into the computations.
- The complexity of the computations to be performed.
- The sixty second cycle period for the controller.
- The accuracy required.

The automation will probably come at extra cost, though the capital expenditure is set off against reductions in staffing requirement. The technical argument for automation is discussed in chapters 4 and 8.

9.6 RELIABILITY AND REDUNDANCY

The assumption for reliability is that the controller hardware will fail. The problem is then how to proceed when the failure occurs. For all critical items in the controller system backups will be provided. The items with backups are shown in Table 9.4. The backups will run all the time concurrently with the first line systems, they are not storage. Running backups in parallel with the main units is currently done in dynamic positioning systems. For other non-critical items, manual backups will be used. In the event of a complete failure, the vessel can always go into a moored mode which is satisfactory. For partial failures, the reaction is a function of what part fails. For failure of the data gathering system human operators can gather the data but the cable lay will proceed at a dead slow speed and the accuracy will be diminished. For a failed data display system, the operators can fall back to the analog inputs on the equipment and the paper copies of the plan. Updates of current corrections and offsets to the prepared plan should be printed every half hour. Again, the speed is reduced and accuracy may be also. For a failed control command system the operators will have to use the analog inputs, and, again, speed will be reduced, the accuracy decreased and the staffing requirements increased. In this way, the failure of the controller system will be an inconvenience but not a problem.

TABLE 9.4

EQUIPMENT LIST

EQUIPMENT	DESCRIPTION	EXAMPLE BRAND	USE ON COM.	USE ON HDWC	REDUNDANT COM.	REDUNDANT HDWC
Navigation	MicroWave	Mini-ranger	Yes	Yes	Yes	No
Vessel Heading	Gyro compass	Honeywell	Yes	Yes	Yes	No
Cable Data:						
Length	Meter Wheel-CHSS	Western Gear	Yes	Yes	Yes	No
Angle	Mechanical	built for	Yes	Yes	Yes	No
Tension	from CHSS	Western Gear	Yes	Yes	Yes	No
Current sensor	Acoustic	Neil Brown	Yes	Yes	Yes	No
Planned Cable Path	Micro Computer #2	a PC	Yes	Yes	Yes	No
Cable Observation:						
Acoustic Marker	Depth & Position		Yes	Yes	Yes	No
ROV	Surface Tethered		Yes	Yes	Yes	No
Controller	High Capacity Micro Computer #1	HP-9817	Yes	Yes	Yes	No
Operators stations	Graphics Computer #3&4	Apple Mac	Yes	Yes	Yes	Yes
Data Acquisition System	Micro Computer #5	HP9826	Yes	Yes	Yes	Yes
Dynamic Positioning System	Dynamic Position	Honeywell	Yes	No	Yes	No
Joy Stick Control	Integrated control	Aquamaster	Yes	Yes	Yes	No
Propulsion Units	Rotatable Thruster	Aquamaster	Yes	Yes	No	No

CHAPTER 10

CONCLUSIONS

10.1 GENERAL

- The objectives of the integrated control system: bottom cable tensions control, bottom cable position control and vessel heading control can be achieved under the severe environmental conditions (2000 m depth, steep slope, high seas, high currents) associated with the Hawaii Deep Water Cable Program.

10.2 TENSION CONTROL

- For proper bottom tension control, a variety of sensors are required including top cable tension, top cable angle, bathymetry data, cable length measurement, vessel position, surface currents and occasional depth and location measurements of the cable on the bottom.

- The conventional method of controlling bottom tension by adjusting the tension at the top is not adequate alone because of the great depth, anticipated dynamic tensions and bottom slopes. In shallower water and less severe seas of the Alenuihaha Channel, this method alone is preferable.

- Monitoring cable angles alone cannot be used for controlling bottom tension because of the large variation in bottom tension relative to small cable angle changes and because of the influence of currents. Cable angle is a good indicator of current influence.

- An alternate method of controlling bottom tension on the basis of measuring the entire geometry (vessel position, bathymetry and cable length) cannot be used alone because of confusion with unknown depth and currents.

- The overall control system has been integrated with the cable tensioning machine control system such that a feedback tension command is provided to the CHSS in order to control cable payout length. At the same time, the linear tensioning machine performs adequately as a heave compensator thereby reducing cable dynamics.

- An automatic control system is recommended whereby the overall controller sends commands directly to the CHSS. The system is continually manually checked and provisions for manual override are provided.

- A review of the various contingency situations results in that no single failure is catastrophic. Critical control items are provided with identical backup hardware.

- Bottom tensions of 4000 kg ± 2000 kg have been assumed to be suitable in this study. Lowering either of these values requires an increase in precision of cable tension measurement and possibly requires the continual monitoring of current profiles while in deep water.

10.3 CABLE POSITION CONTROL

- Cable position control is achieved by vessel position control. The main difference between straight line vessel course and cable path is cable offset due to currents. Depending upon the accuracy of cable placement, these current offsets must be appropriately measured.

- Cable offsets due to current can be determined by monitoring surface cable angles and with occasional acoustic updates of cable position on the bottom.

- In 2000 m of water the maximum cable offset under the maximum current profile is 400 m.

- If precise cable placement is required to avoid bottom obstacles, a prelaid wire rope is recommended and the cable should be laid following this wire rope with the assistance of a remote operated vehicle. Such an operation in deep water is well beyond the operational state of the art of cable laying; the primary uncertainties at this time are cable shifts due to unsteady currents and the complexity of the path that needs to be followed. At this time, the requirement for such precise positioning has not been established.

- Vessel positioning can be based on a computer aided display of the desired vessel course and actual vessel position. The thrusters are manually controlled. Speed and heading are selected by the operator.

- A fully automated dynamic positioning system is possible at a cost exceeding $500,000 but is not technically needed unless precise cable placement is required.

10.4 NAVIGATION

- Microwave range-range navigation systems are the lowest cost systems capable of accuracies at ±3 m.

- The navigational system is crucial to the proper placement and tensioning of the cable; a full redundancy of all components is recommended.

- Within the Hawaiian chain, there are adequate locations for shore repeater stations such that there is adequate accuracy and coverage over the entire cable route. They are routinely used in Hawaii.

10.5 <u>VESSEL PROPULSION</u>

- A 3-D equilibrium model of the environmental and task related loads on a cable-laying vessel have been developed. Thrust vectors required to balance the equilibrium loads are obtained with this model. The cable touchdown point (excursion and distance) along the equilibrium bottom path is also obtained.

- Propulsion requirements for the baseline vessel to follow a prescribed path and lay cable along the equilibrium path under the Alenuihaha Channel baseline environment have been established. The major loads on the vessel are from surface currents at 1.5 m/s (3 kts).

- Propulsion Systems (Tugs, Fixed and Rotatable Thrusters) meeting these requirements have been identified and documented. The following should be assumed for these systems:

Static Thrust Delivered / Rated Power	:	149 N/kW (25 lbs/HP)
Capital Cost / Rated Power	:	120 $/kW (90 $/HP) for Fixed Thruster;
		160 $/kW (120 $/HP) for Rotatable Thrusters.
Engine Cost / Rated Power	:	160 $/kW (120 $/HP) for Rotatable Thrusters.

- Cost associated with the rental of Tugs and Barges of the appropriate dimensions and power range have also been documented. Fixed or Rotatable Thrusters of the required nominal power are not usually available for lease or rent.

- Based on the rental cost of tugs, the capital and installation costs for thrusters and the time required for deploying the full commercial system, it is clearly cost effective for the commercial system to install rotatable thrusters on the deployment barge.

- Several configurations of thrusters and tugs were conceptualized and evaluated. Thrusters installed on the barge are clearly technically superior in terms of operational sea state, proper application of power, control and maneuverability.

- A system of two rotatable thrusters with nominal power of 2240 kW (3000 HP) each is recommended for the commercial system.

- For the HDWC Demonstration program, two rotatable fixed thrusters identical to the commercial system are also recommended. Although it is less expensive to utilize tugs for this demonstration, the test would be compromised by not operating under high sea states and large currents. In addition, precise laying of a cable would be impossible and a different control system would be required than that for the commercial system.

10.6 VESSEL HEADING

- Vessel heading is restricted by deflection of the cable at the overboarding sheave. Top cable angle measurements must be made in order to display to the operator heading limitations.

- The 10° angular deflection limitation at the sheave, including roll, severely restricts vessel heading. It will be difficult for the control system to maintain these restrictions at all times, particualrly under contingency situations.

10.7 ENVIRONMENTAL INFORMATION

- The primary environmental information required by the control system is bathymetric data. Current bathymetric data is insufficiently accurate for the commercial cable laying operation. General bathymetric information with 10m contours is required.

- Areas of precise cable location, if they exist, need to be identified and characterized. If such areas exist, they strongly influence the extent and cost of the integrated control system.

- Any cable route selected should avoid laying the cable parallel to steep slopes. An alternate cable path has been recommended avoiding these conditions along the southern coast of Maui and below Molokai.

- Cable angular measurement at the surface is critical for cable placement accuracy and proper cable tensioning. No commercial system has been identified for measuring this three-dimensional angle. However several systems have been proposed. The appropriate hardware must be developed and fabricated.

10.8 BOTTOM CABLE LOCATION

- A surface oriented acoustic system can adequately locate transponders on the bottom cable to an accuracy of 1% of the depth. This is an adequate accuracy for cable tensioning and most cable placement operations even in the Alenuihaha Channel.

- One remote operated vehicle is available which can operate at the bottom of the Alenuihaha Channel. Its maximum speed capability is .25 m/s (1/2 kt). This vehicle could be used for precise cable placement, inspection and surveying.

10.9 CONTROLLER

- Equipment to make up the controller can be found off the shelf. Systems handling more complex problems with more communications exist.

- The controller should be fully automated to maintain cable tension within tight tolerance at the deeper depths.

- The controller should be semi-automated determining vessel course at the tightest cable path tolerances. The manual input would adjust the computer course for ROV observations.

- The controller is comprised of two minicomputers. The main computer interfaces with the sensors and performs primary computations. The second computer interfaces with the operator.

- The Data Acquistion System requires a separate computer and is independent of the primary controller.

- Computer power in terms of data sampling and computation is not large. A small but fast micro is capable of the job.

- Full redundancy for the controller is recommended for the commercial lay operation. For the HDWC operation, full redundancy is probably not worth the added cost.

10.10 HDWC PROGRAM CONTROLLER TEST RECOMMENDATIONS

- A full control system should be used with the HDWC program with the exception that some of the redundancy can be relaxed.

- Total cable geometry from the deployment vessel should be verified by monitoring the cable touchdown point by surface acoustic positioning, cable profile by surface acoustic positioning and fully recording all vessel sensors. During testing, current profiles should be made in order to tie in current loads with cable position. Such data could be used to obtain drag coefficients for the vibrating cable. The actual versus the computed cable placement on the bottom should be determined utilizing acoustic positioning systems. The accuracy of the cable laying algorithms could then be determined.

- The external feedback control system for the linear tensioning machine should be exercised along steep slopes and under high sea states.

10.11 EQUIPMENT REQUIRED

EQUIPMENT LIST

EQUIPMENT	DESCRIPTION	EXAMPLE BRAND	USE ON COM.	USE ON HDWC	REDUNDANT COM.	REDUNDANT HDWC
Navigation	MicroWave	Mini-ranger	Yes	Yes	Yes	No
Vessel Heading	Gyro compass	Honeywell	Yes	Yes	Yes	No
Cable Data:						
Length	Meter Wheel-CHSS	Western Gear	Yes	Yes	Yes	No
Angle	Mechanical	built for	Yes	Yes	Yes	No
Tension	from CHSS	Western Gear	Yes	Yes	Yes	No
Current sensor	Acoustic	Neil Brown	Yes	Yes	Yes	No
Planned Cable Path	Micro Computer #2	a PC	Yes	Yes	Yes	No
Cable Observation:						
Acoustic Marker	Depth & Position		Yes	Yes	Yes	No
ROV	Surface Tethered		Yes	Yes	Yes	No
Controller	High Capacity Micro Computer #1	HP-9817	Yes	Yes	Yes	No
Operators stations	Graphics Computer #3&4	Apple Mac	Yes	Yes	Yes	Yes
Data Acquisition System	Micro Computer #5	HP9826	Yes	Yes	Yes	Yes
Dynamic Positioning System	Dynamic Position	Honeywell	Yes	No	Yes	No
Joy Stick Control	Integrated control	Aquamaster	Yes	Yes	Yes	No
Propulsion Units	Rotatable Thruster	Aquamaster	Yes	Yes	No	No

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APPENDIX 1.

CABLE LOCATING ACOUSTICS

Bi-Directional Acoustic Data Transmission

The Oceano Instruments DT 122 is a high integrity acoustic serial data transmission system for digital data communication between subsea units or between the surface and seabed instrumentation.

Typical applications include real time bi-directional data transmission between ships and submersibles, wellhead control, seabed instruments data transmission, subsea production control and untethered ROV control.

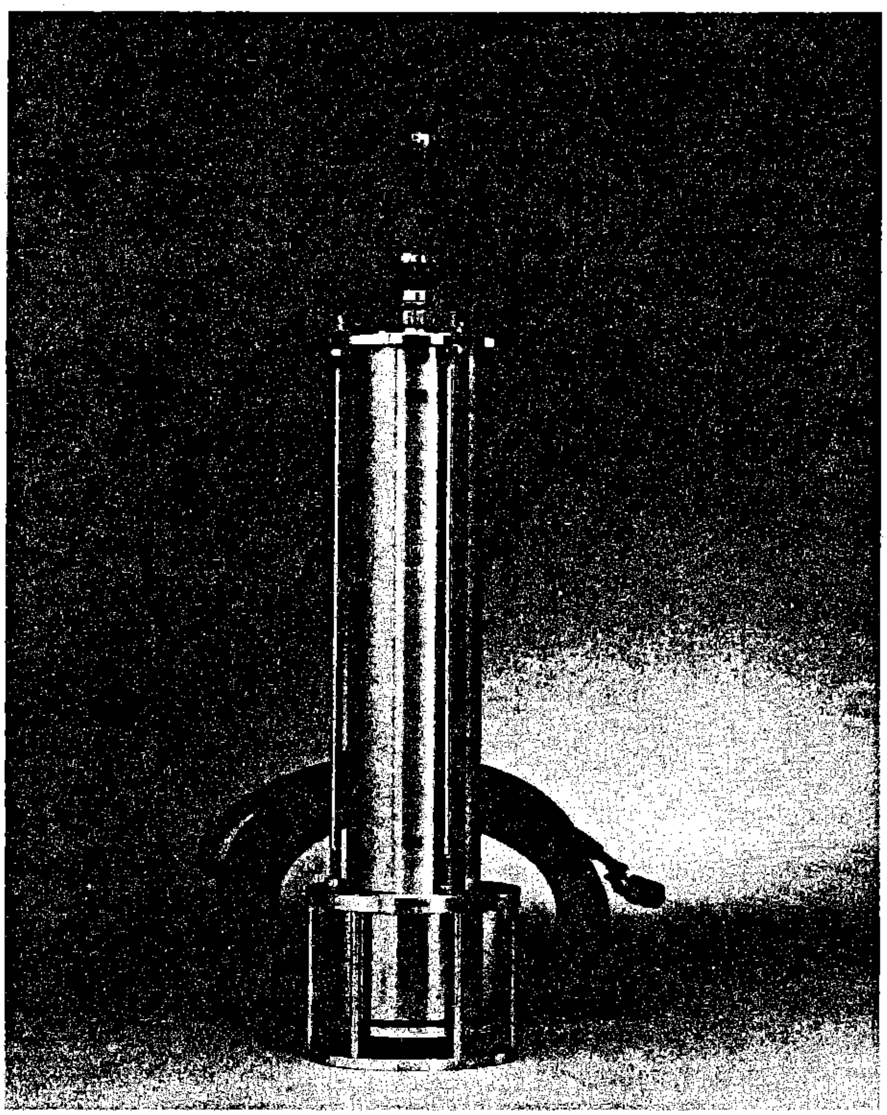
With offshore operations moving into deeper water, hard wired connections to subsea instruments or control valves are becoming increasingly less feasible. The DT 122 is a practical alternative.

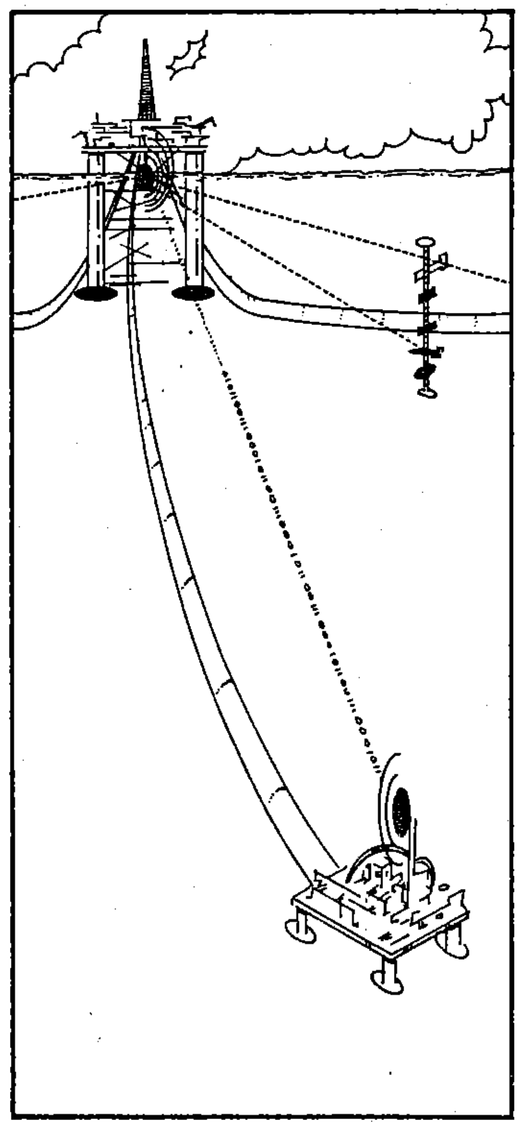
The system contains an identical pair of DT 122 units which are able to receive and send data to each other through water using a secure form of FSK coding. Cyclic redundancy is built in for reliable operation and immunity against multipath effects.

A binary message generated outside the system is translated into a secure, redundant code and acoustically transmitted by the first DT 122. The second DT 122 translates this message back into binary code for action by the appropriate equipment.

The DT 122 uses FSK-NRZ4 (Frequency Shift Keying, Non Returning Zero, four Frequency) as its transmission mode. To begin a transmission sequence, one DT 122 transmits a unique frequency primary synchronization pulse, with at least one octet of special code. Surface and bottom DT 122's use two separate primary synchronization pulse frequencies. This allows a unit to receive immediately after transmission without fear of multipath induced error.

Optional parameters on the DT 122 include directional or hemispherical transducers, stainless steel or cuproaluminum housings, variable power input and acoustical level output. The data rate is adjustable from 80 to 320 BAUD per second.





APPENDIX 2.

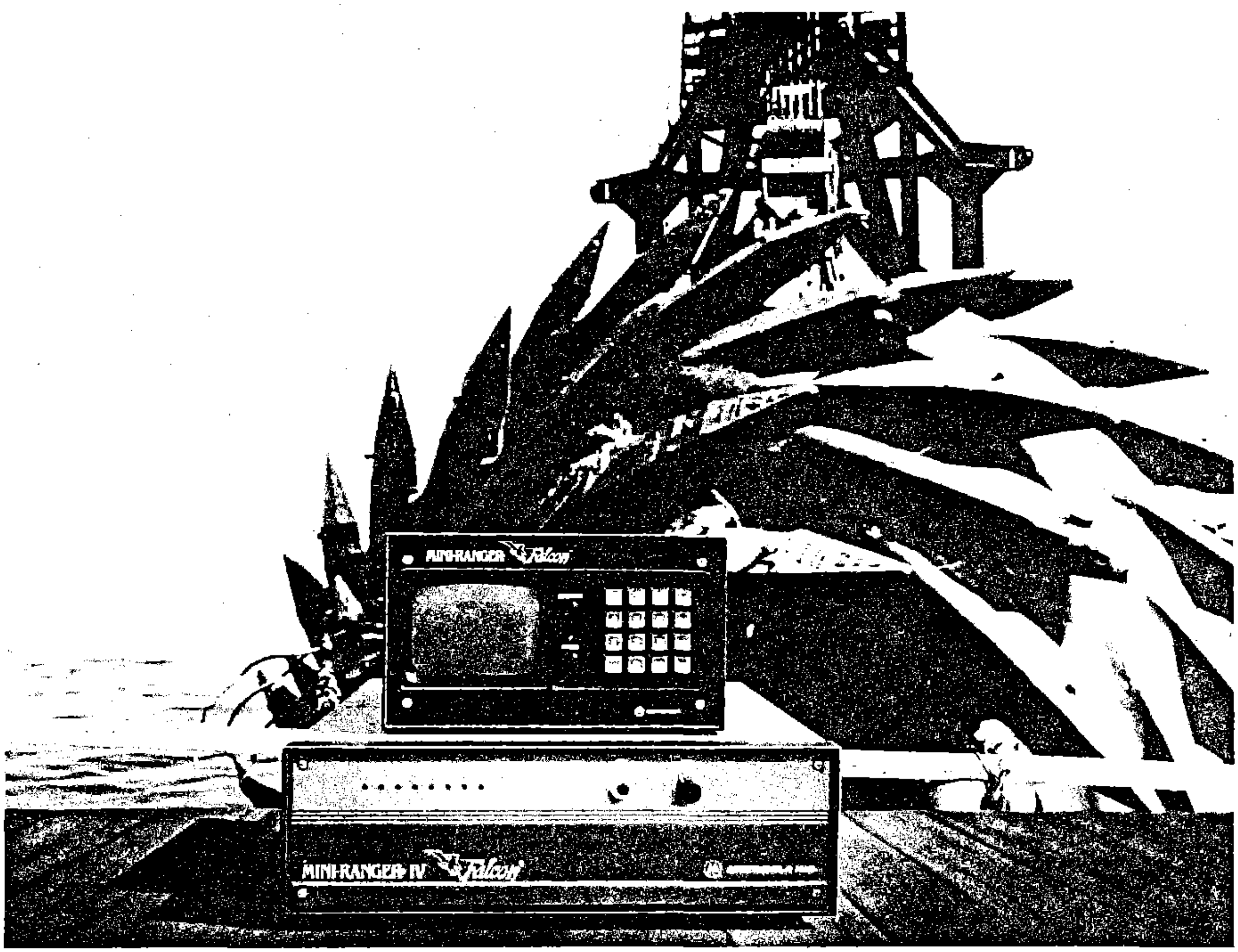
NAVIGATION BROCHURES

MINI-RANGER Falcon IV

positioning system

PRODUCT DESCRIPTION

AUGUST 1983



MOTOROLA

MINI-RANGER Falcon IV

THE MINI-RANGER FALCON IV TURNKEY POSITIONING SYSTEM

The Falcon IV is the heart of a completely automated positioning system. The Falcon IV, when combined with a track indicator, track plotter, tape recorder, printer, and an echo sounder, provides the user with the most cost-effective, dedicated positioning system available today with, by far, the most standard features.

The standard Falcon IV is configured with multi range position solution firmware, supplying rectangular coordinates of the solved position. The same survey program will preplot charts; provide real time steering information, data storage, and track plotting of your course; and in post process will also provide finished charts with digitized depth and/or event data if that information has been supplied to the Falcon IV.

The Falcon IV fits a wide range of applications: hydrographic surveying, dredge positioning, seismic ship positioning, oil rig positioning, and airborne geophysical surveys just to mention a few.

Field proven performance has established the Falcon IV as the versatile standard for automated positioning.

SYSTEM FEATURES

Space Diversity Control

One performance-limiting phenomenon occuring when radar energy is transmitted over water is the phase subtraction at a receiving antenna caused by pulse reflection from the water surface. Reflection causes a difference in path length (and phase) resulting in signal energy cancellation at the receiving antenna.

The area over which significant cancellation may occur is mathematically predictable and is known as a "Range Hole."

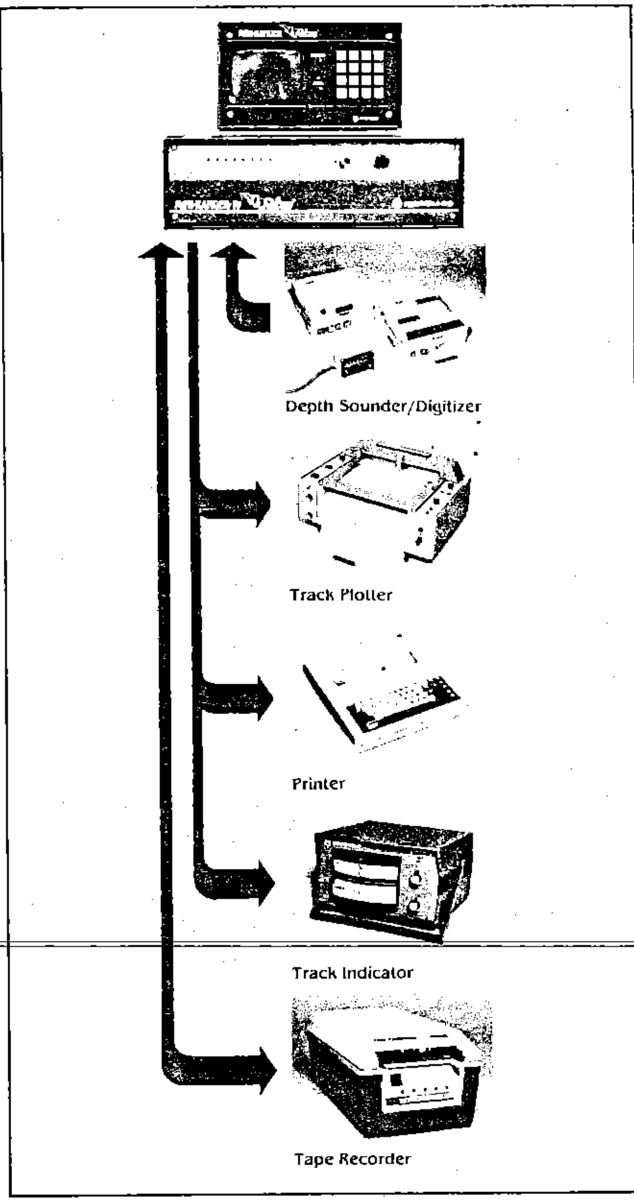
The technique to avoid phase cancellation is to install a second receiver, displaced vertically so that the cancellation effects are at a minimum when the first receiver is experiencing maximum subtraction.

The purchase of the second receiver and cable is optional. The control of the system to accomodate space diversity is standard in Falcon IV.

Peripheral Interfaces

Interface provisions for the Control Display Unit (CDU), Track Indicator, Tape Recorder, Track Plotter and Printer are standard.

Optional interfaces for a Depth Digitizer, Event Mark, and auxiliary BCD data, are available at nominal cost to complete your Falcon IV positioning system.



Built-in Test Equipment

Mini-Ranger has historically used the BITE concept wherever possible to help you with fast and accurate field troubleshooting.

Falcon IV BITE is implemented with hardware and software containing capabilities for detecting functional problems in RF and range processing. Performance problems are sensed and displayed on the CDU.

The Falcon IV Range Processor also has front-panel-mounted status lights indicating overall range processor and RF system function status.

The combination of Range Processor and Universal Reference Station BITE functions leads the industry in rapid, accurate, fault isolation capability.

Accurate Multi-Range Position Solution

Falcon IV is capable of measuring line of sight ranges from 100 meters to 75 kilometers, day or night, in all weather conditions. Falcon IV's positioning performance advantage is in its ability to automatically measure multiple ranges, under self-contained microprocessor control, and to use them in an effective least squares position algorithm. The Falcon IV position algorithm will solve for position with 2, 3, or 4 range outputs sensed from any of the 16 possible Universal Stations whose locations have been entered in EE PROM from the Range Processor.

Individual range measurement probable range error is less than ± 2 meters. When these precise ranges are processed in the full multi-range mode, position accuracy, while still geometry-dependent, approaches range accuracy.

Multi-User

Firmware-implemented multi-user allows time-shared use of the same operating area by up to 20 users, providing essentially interference free operation in a high-density environment.

Selectable System Measurement Units

The Falcon IV Range Processor allows the operator to select meters, feet, or yards for units of measure. This permits the operator to match the system to the application.

Range Quality Control

Range residuals, sum-of-squared residuals, and error-circle-radius data are calculated by the least squares solution. This data, along with signal strength data for each range, is used to provide error indications if range quality drops below operator-selectable limits.

Signal Strength Monitoring

The acquisition of multiple valid ranges is an important factor in obtaining a good x-y position. Valid ranges are characterized in a number of ways: one is by signal strength. If line of sight should be interrupted for some reason, or if a nonspace diversity system should encounter a "range hole" between the R/T and Reference Station, that expected range input to the position solution is lost. Although the position will be automatically calculated with 2, 3, or 4 valid ranges, the most accurate solutions are with 4 ranges.

48 Code

The Falcon IV Range Processor is capable of addressing 48 reference station codes. Up to 16 of these codes may be stored in EEPROM for real-time site selection without data loss. The Universal Reference Stations have 16-code operation standard, with 48-code operation optional.

Depth Processing

Depth data can be input up to 10 times per second. The system will record either (1) the maximum, minimum and mean depth collected during the sample period, or (2) a spot depth at the sample point. These recorded values are not corrected for tide or draft.

The real-time display of depth on the CDU or attached terminal will be corrected for draft and tide. In post process, the system uses either entered or recorded draft data, and either the recorded tide data or a tide table to correct the depth when plotting a chart. The optional dredge volume software will draw a profile of the depths on a line against an ideal profile and will compute the underdredge and overdredge volumes for a surveyed area.

SYSTEM ELEMENTS

Range Processor

The Falcon IV Range Processor features a powerful MC 6809 microprocessor combined with a 150 MHz range clock to assure maximum data output quality. The processor has a memory capacity of 120 kilobytes of EPROM, EEPROM, and RAM. It provides 40 bit binary precision, plus 8 bits of exponent and sign, and multi-range position update rates of 1 sec. The range processor utilizes a bus-organized, modular design approach to ensure reliability and maintainability.

Interactive Control and Display

The Falcon IV CDU, with its 5-inch CRT and function keypad, is the truly effective control element providing fully interactive system communication. Easy-to-see red CRT alphanumerics lead the operator through system initialization with step-by-step prompting routines. Then the CDU gives an alphanumeric view of system performance throughout the entire mission. The CDU is a compact unit easily mounted in the most restricted of spaces. The CDU may be operated adjacent to the Range Processor or remotely.

Ranging Components (R/T's and Reference Stations)

The Falcon IV System utilizes and is compatible with all existing Universal Reference Stations and receiver-transmitters. The field proven reliable reference stations operate at C-band (5400-5600) MHz, which eliminates interference from common marine radars operating at X-band. The highly portable reference stations operate unattended on a pair of automobile batteries or with a self-contained rechargeable battery option. Each unit answers to interrogations with its own unique code which can easily be changed in the field.

FALCON IV SYSTEM PERFORMANCE SPECIFICATIONS

MULTI-USER CAPACITY	20 Users Time-Shared (50 msec/User)
SAMPLE INTERVAL	Time-Based: 1–99 seconds Distance-Based: Projected or Actual, 5–9,999,999 units
TIME OF DAY CLOCK	Crystal Controlled 24-Hour
SIGNAL STRENGTH	Numerical Value From 0–99 Based On Reply Pulse Return Signal Strength
SPACE DIVERSITY CONTROL	Automatic switching between R/T 1 and R/T 2 based on strongest reply pulse signal strength. (Additional R/T required.)
UNITS OF MEASURE	Meters/Feet/Yards (Selectable)
BUILT IN TEST	Troubleshooting capability to the board level.
NON VOLATILE MEMORY	Electrically Erasible PROM (EEPROM).
RANGING OPERATION	
Interrogation Codes	Range Processor: 48 Universal Reference Stations: 16 (48 Code Optional)
Interrogation Modulation	3-Pulse

(continued)

Operating Active Sites	4 maximum
Limits	100 m to 37 kilometers (74 kilometers Optional)
Accuracy	+/− 2 m Probable
Resolution	0.1 m
Calibration	Digital (For each R/T and R/S)
Range Counter Clock	150 MHz (1.0 m Real-time precision)
Acquisition Time	One range per 1.667 msec; 35 msec maximum per system cycle
Range Processing	
Screening	15 m wide tracking window (selectable W = 1 to 99)
Averaging	Selectable quantity per system cycle (Max = 20/N, N = No. of active sites)
Grid Correction	0.80000 to 1.009999 on horizontal
Error Flags	Low signal strength, no range from site
Propagation Velocity	N = 320 (Selectable N = 0 to 600)

X-Y POSITION OPERATION

Position Calculation	Least squares for 3–4 range lines Trilateration for 2 range lines (Automatic switching based upon active ranges lines)
Position Resolution	1.0 m
Reference Site Entry	
Resolution	1.0 m
Quantity	16 stored in EEPROM
Site Change	Real-time without data loss
Reference Line Entry	
Resolution	1.0 m
Quantity	20 Stored in EEPROM
Offsets	±9,999,999 System units
Offset Change	Real-time without data loss
Position Processing	
Least Squares Algorithm	Selectable Residual Screening (SSR) Selectable Variance Screening (ECR)
Tracking Loop	Second order predictive (constant velocity) Filter constants selectable Position tolerance selectable
Error Flags	Range residuals, position variance, tracking loop
Display Format	X-Y Position; Ranges; Chainage-Offset
Display Ratio	1–99 of Sample Interval

PERIPHERAL OPERATION

Track Plotting	(Plotter Optional)
Typical Plotters	H.I. D.P.3, C.P.S. 20, C.P.S. 30
Scale	1 : 100–9,999,999
Plot Reference Line	Selectable from non-volatile Lines
Preplot	Track Lines, with or without Coordinates or Line Number Grid Plot
Real Time	Vessel Position, with Event
Post Plot	Data along Track (Depth, Auxiliary BCD Data), Events
Profile	Track Profile (Volume Profile optional)
Events	Manual, Auto Increment, Decrement Event Number 0–9999 Based on Time or Distance
Optional Event Output	Relay Closure (4A 30V D.C. 1A 115 A.C.) TTL pulse

(continued)

Tape Recording	(Tape Unit Optional)
Typical Recorder	Tek 4923 3M cartridge
Real Time Format	
Control Block:	Site Data, System Units, Track Line Offset, Draft, Tide, Refractive Index, Grid Correction
Data Block:	Time, X-Y Position, 4 Ranges, Signal Strength, Depths, Auxiliary Input, Tide, Event Number
File Number	0–19,999,999 File Search, List Data
PRINTER (OPTIONAL)	
Typical Printer	T.I. 743 KSR
Real Time Format	Time, X-Y Position, Depths, Auxiliary, Events
Print Ratio	1–99 of Sample Interval (Minimum 2 seconds)
List Data	Site and Line Data Calibration Table Post Process Listing
TRACK INDICATOR (OPTIONAL)	
Display	Analog Left/Right of Track Line, Offset 5, 20, 80 Units Per Division Analog Percentage of Chainage along Track line
DEPTH INPUT (OPTIONAL)	
Input	5 Digits B.C.D. Fixed Format XXXX.X, Read Flag Maximum 10 Per Second.
Minimum Input Limit	0–999,999.9 Selectable
Draft Correction	0–999,999.9 Selectable
Tide Correction	±999,999.9 Selectable
Depth Processing	Maximum, Minimum, Mean Per Sample Period Spot Depth at Sample Time
Tide Table	Post Process 20 Points
VOLUME (OPTIONAL)	Underdredge/ Overdredge Volumes

AUXILIARY INPUT (OPTIONAL)	
INPUT	5 Digits B.C.D. Fixed Format, XXXX.X, Read Flag
Sample	One at Sample Time

FALCON IV ELECTRICAL AND PHYSICAL SPECIFICATIONS

RANGE PROCESSOR	
INPUT VOLTAGE	
AC	115/230 +/− 10% VAC (47–420 Hz)
DC	20–32 VDC
INPUT POWER	150 Watts (Range Processor with CDU and R/T)
SIZE (Hwd)	14 × 46 × 43 cm
WEIGHT	17 kg
OPERATING TEMPERATURE	+0° to +50°C
CONTROL DISPLAY UNIT (CDU)	
INPUT VOLTAGE	Powered from range processor
SIZE (Hwd)	16 × 28 × 28 cm
WEIGHT	4.5 kg
OPERATING TEMPERATURE	+0° to +50°C
DISPLAY	5-inch CRT Alphanumeric, red phosphor, EIA Composite Video for remote CRT monitor drive
RANGING COMPONENTS	
RECEIVER TRANSMITTER (R/T)	
Frequency	5400–5600 MHz (C-band)
Antenna	6 dB omni-directional (25° elevation)
Operating Temperature	−35° to +60°C
Power	Supplied by range processor
Size (Hwd)	31 × 21 × 17 cm
Weight	4.5 kg

(continued)

UNIVERSAL REFERENCE STATION (URS)	
Frequency	5400-5600 MHz (C-band)
Antenna	13 dB sector (70° Azimuth, 15° elevation) for 37 kilometer range 19 dB sector (70° Azimuth, 5° elevation) for optional 74 kilometer operation
Operating Temperature	−35° to +60°C
Operating Voltages	22–32 VDC
Power	13 watts nominal, 8.5 watts standby
Size (Hwd)	31 × 21 × 17 cm
Weight	4.5 kg

FALCON IV ORDERING INFORMATION

DESCRIPTION	ORDER PART NUMBER
Mini-Ranger Falcon IV – 20 nmi System (37 kilometers) Includes	01-P06841Y001
Falcon IV Range Processor	
AC & DC Power Cables	
Mating Connectors	
O&I/Maintenance Manual	
Control Display Unit (CDU)	
Interconnect Cable – 25Ft Video Monitor Manual	
Cable – Slimline (RP-R/T 1) – 25Ft	
Reference Station (2 ea.)	
DC Power Cables	
Mounting Bands	
13dB Sector Antenna	
Receiver Transmitter	
Mounting Bands	
6dB Omni Antenna	
Mini Ranger Falcon IV 40 nmi System (74 Kilometers) includes the 20 nmi System with	01-P06841Y001 w/Option 27U
19 dB Sector antenna (2 ea.) substituted for 13 dB antennas	
OPTIONS – FALCON IV – RANGE PROCESSOR	
Depth (Including mating connectors)	Option 612
Dredge Volume Program	Option 620
Auxiliary Input (Including mating connectors)	Option 608
Event Mark Module	Option 629
Space Diversity Includes Receiver/ Transmitter and Space Diversity Cable (25Ft Slimline)	Option 625
Special Receiver/ Transmitter Cable Lengths	
Regular R/T Cable Lengths to 1000 ft.	Consult Motorola
Slimline R/T Cable Lengths to 100 ft.	Consult Motorola
Rack Mounts And Cases	
Rack Adapter 19-inch	Option 617
Rack Adapter w/slides 19-inch	Option 680
Ruggedized Case (Includes Rack Adapter)	Option 609
SHIPPING CASE – CDU	56-P03177J001
SHIPPING CASE – RANGE PROCESSOR	56-P03176J001
SHIPPING CASE – R/T's & UNIVERSAL REF. STATION	56-P03177J001

(continued)

FALCON IV ORDERING INFORMATION (CONT.)

DESCRIPTION	ORDER PART NUMBER
OPTIONAL PERIPHERALS	
Terminals	
Terminal TI-743ksr 115vAC 60hz	78-P01087U004
Terminal TI-743ksr 230vAC 50–60hz	78-P01087U021
Tape Recorder Kit	
TEK-4923 Cartridge Tape Recorder	78-P01087U003
Plotters	
Plotter CPS-20/1CA (.01 In)	78-P01087U024
Plotter CPS-20/1CAM (.25mm)	78-P01087U025
Plotter CPS-30/1CA (.01 In)	78-P01087U022
Plotter CPS-30/1CAM (.25mm)	78-P01087U023
Plotter DP-1E-1H-3V	78-P01087U002

DESCRIPTION	ORDER PART NUMBER
Inverters	
Inverter 12vdc/115vAC 300 watts	315-B-12
Inverter 12vdc/230vAC 300 watts	1057-12
Inverter 24vdc/115vAC 300 watts	315-B-24
Inverter 24vdc/230vAC 300 watts	1057-24
Depth Sounders/Digitizers	
Depth Sounder – Raytheon 719B	719B
Digitizer – Raytheon SSD-100	SSD-100
Digitizer – Innerspace 412	412
Simulator – Depth	01-P03780R001
Track Indicator Kit Includes 25 Ft Interface Cable	01-P01135U001

MINI-RANGER Falcon IV

UNITED STATES

ALABAMA
Huntsville - Kemp Instruments
Telephone: (205) 837-4304

ARIZONA
Phoenix - Cleveland Enterprises of Arizona
Telephone: (602) 820-1127

CALIFORNIA
Los Angeles - Whitney
Telephone: (213) 595-0391

San Diego - Whitney
Telephone: (619) 481-3222

COLORADO
Denver - Pond Associates
Telephone: (303) 798-2904

DISTRICT OF COLUMBIA
Washington - Gans & Pugh
Telephone: (703) 527-3262

FLORIDA
Jacksonville - Tool-Tronics Hydrospace
Telephone: (904) 268-2699

Miami - Tool-Tronics Hydrospace
Telephone: (305) 226-2630

Tampa - Tool-Tronics Hydrospace
Telephone: (813) 782-7177

GEORGIA
Atlanta - Kemp Instruments
Telephone: (404) 452-8050

ILLINOIS
Chicago - Dytec/Central
Telephone: (312) 394-3380

INDIANA
Indianapolis - Dytec/Central
Telephone: (317) 247-1316

LOUISIANA
Lafayette - Kemp Engineering
Telephone: (318) 269-9452

MARYLAND
Baltimore - Gans & Pugh
Telephone: (703) 527-3262

MASSACHUSETTS
Boston - McCarthy
Telephone: (617) 383-0720

MICHIGAN
Detroit - WKM Associates
Telephone: (313) 588-2300

NEW YORK
Centerport - Lindgren
Telephone: (516) 423-7734

OHIO
Cleveland - WKM Associates
Telephone: (216) 524-5930

Dayton - WKM Associates
Telephone: (513) 434-7500

OKLAHOMA
Tulsa - Kemp Engineering
Telephone: (918) 663-4501

PENNSYLVANIA
Pittsburgh - WKM Associates
Telephone: (412) 892-2953

TEXAS
Dallas - Kemp Engineering
Telephone: (214) 931-7100

Houston - Kemp Engineering
Telephone: (713) 466-1465

VIRGINIA
Arlington - Gans & Pugh
Telephone: (703) 527-3262

WASHINGTON
Seattle - Jon B. Jolly
Telephone: (206) 938-4166

WORLDWIDE REPRESENTATIVES

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GERMANY, Rolandseck
Motorola GmbH
Telephone: (02228) 7026

ITALY, Rome
Motorola S.p.A.
Telephone: (06) 877007

JAPAN, Tokyo
Motorola MAE
Telephone: (03) 440-3311

MALAYSIA, Selangor
Motorola MAE
Telephone: (03) 758444

NETHERLANDS, Utrecht
Motorola B.V.
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Motorola representatives are also headquartered in these major cities around the world:

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Buenos Aires
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Copenhagen
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Jakarta
Karachi
Lima
Lisbon
Ljubljana
Madrid
Manila
Mexico City
Montevideo
New Delhi
Oslo
Panama City
Paramaribo
Paris
Port-of-Spain
Reykjavik
Rio de Janeiro
Santiago
Seoul
Stockholm
Sydney
Taipei
Toronto
Wellington

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SAN DIEGO 619-481-3222
SIGNAL HILL 213-595-0391

5106 8/83 - 10/83

APPENDIX 3.

TECHNICAL DESCRIPTION OF AVAILABLE TUGS

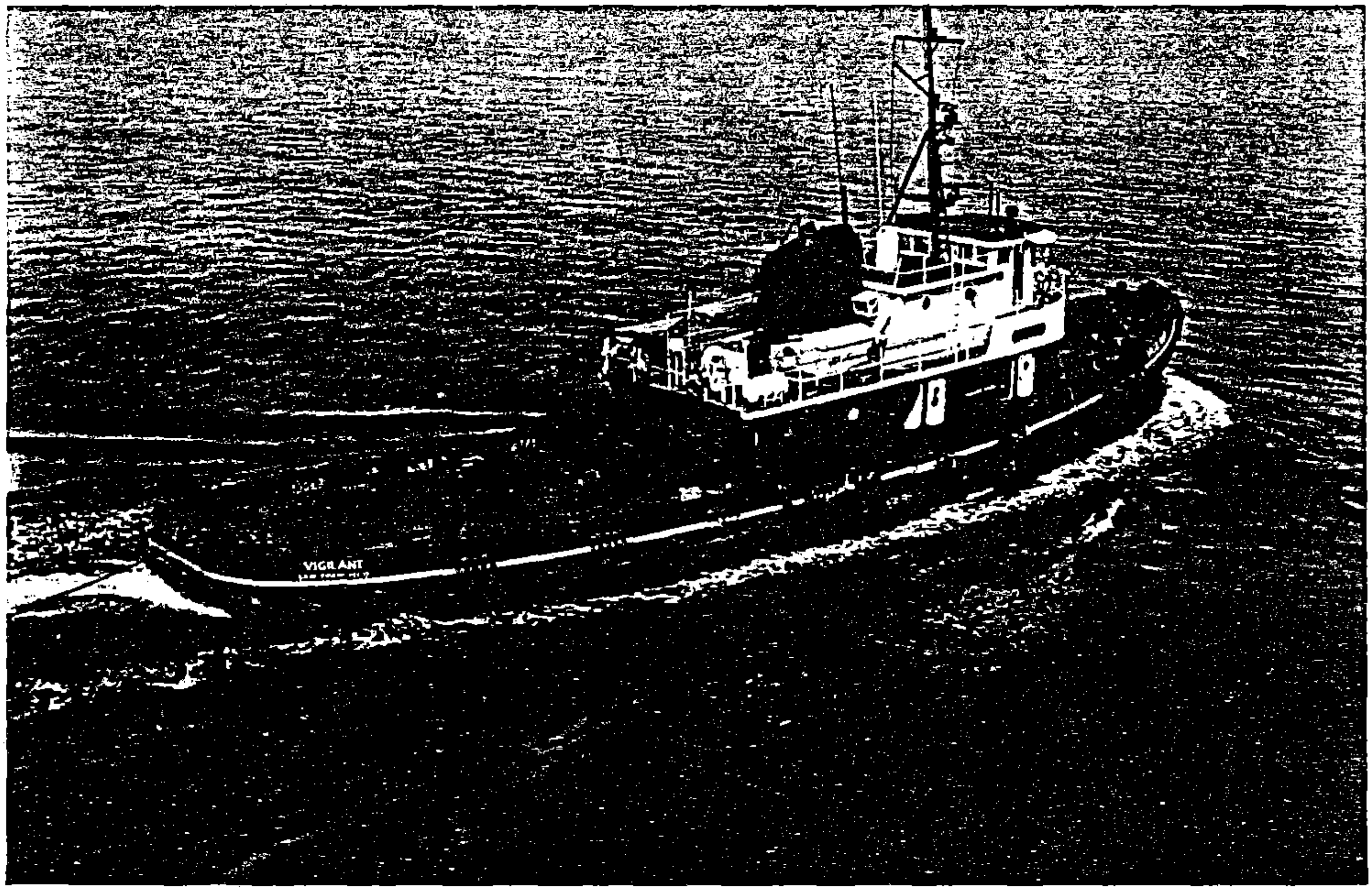
APPENDIX

Technical Descriptions of Available Tugs

Compare to Daring class, bigger engines

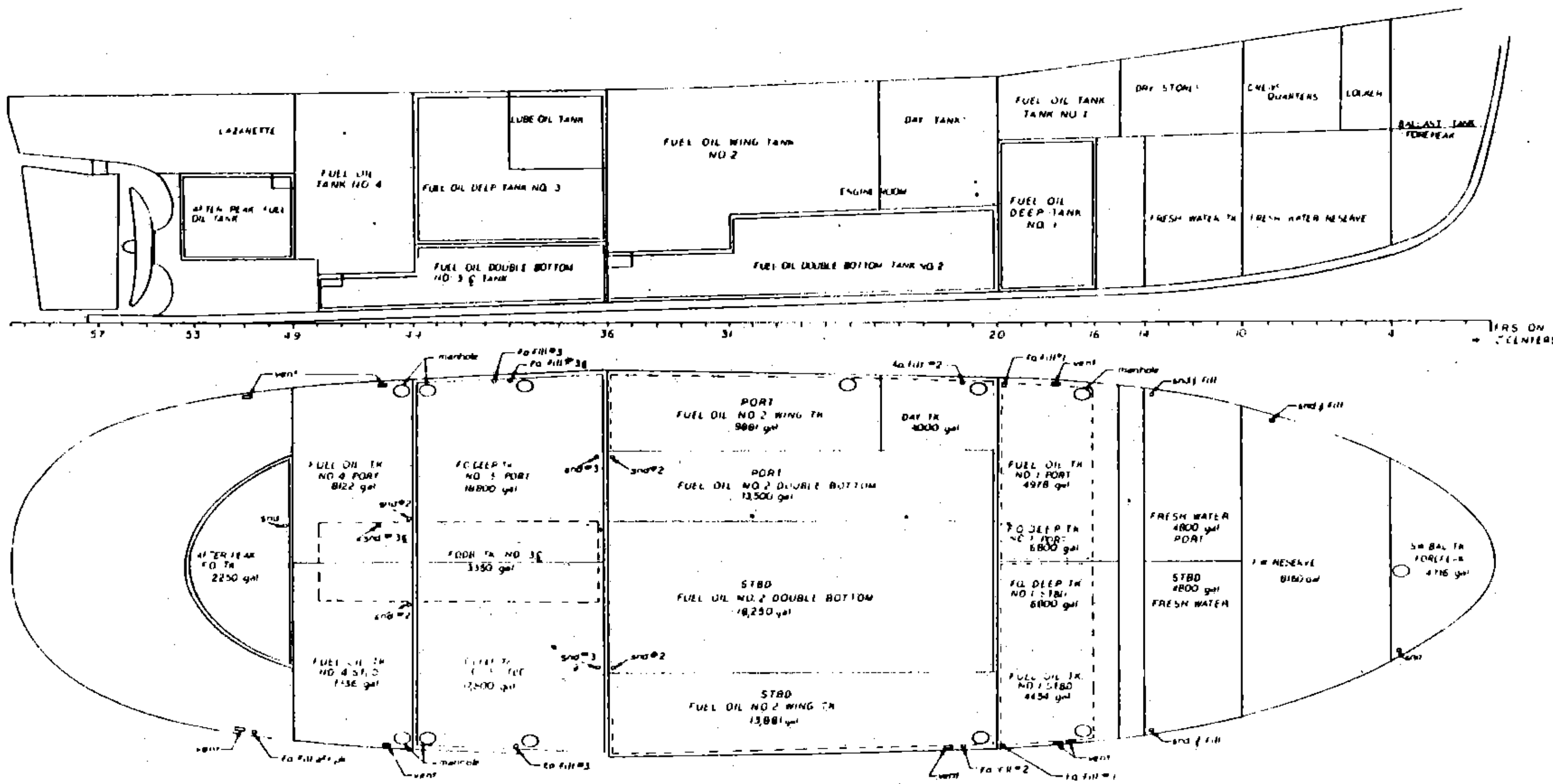
SEA RACER CLASS

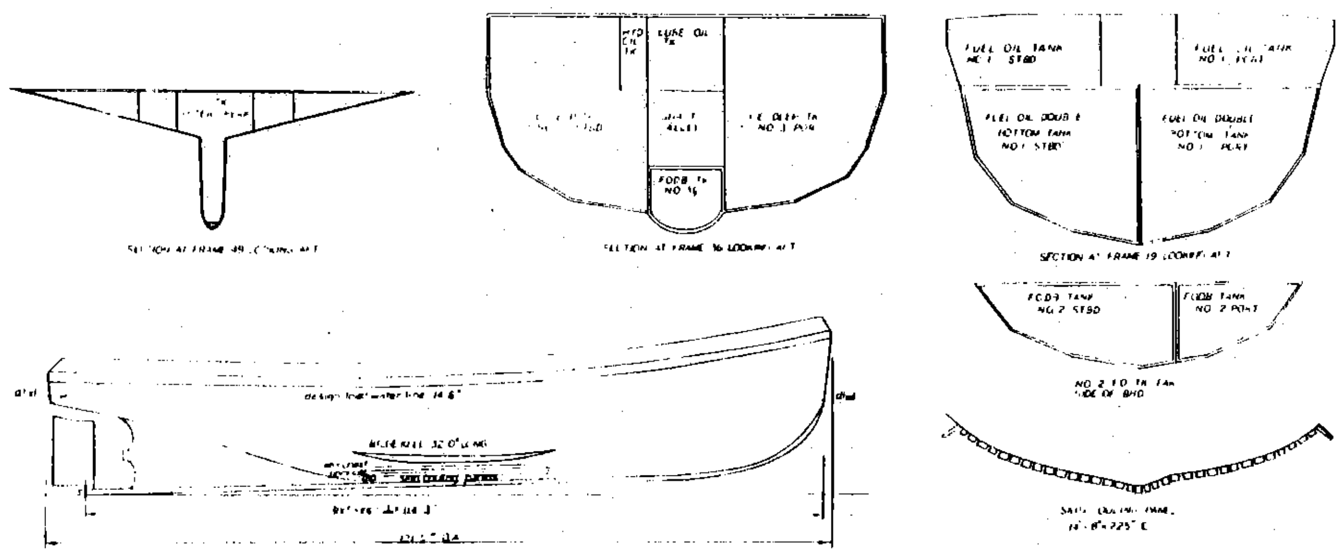
SAMSON	1966	SEA RACER	1966
SEA MONARCH	1966	VIGILANT	1966



DIMENSIONS: 121′ x 32′ x 13′
ENGINE: EMD 16-645-E5
HORSEPOWER: 3,500
FUEL: 100,000 gallons

LUBE: 2,200 gallons
WATER: 18,000 gallons
AUXILIARIES: (2) CAT D-333
(2) 60KW, 120/208V





COMPARTMENT	CAPACITY GAL	TONNAGE	DEPTH
FORE PEAK BALLAST (G#1)	4716	202	
FRESH WATER RES	8[illegible]	34.[illegible]	13' 6"
" " PORT	48[illegible]	20.[illegible]	15' 6"
" " STBD	48[illegible]	[illegible]	11' 6"
F.O. PORT NO 1	4970	17.5	[illegible]
" " " DP TK	6800	25.8	[illegible] 6"
" STBD " 1	4454	15.7	5' 3"
" " 1 DP TK	68[illegible]	25.[illegible]	[illegible] 6"
" PORT " 2 WG TK	9981	34.8	15' 5"
" " " 2 DB BT	135[illegible]0	47.3	6' 6"
" STBD " 2 WG TK	13881	48.8	13' 3"
" " " 2 DB BT	18[illegible]0	63.9	7' [illegible]
" PORT 3 DP TK	18800	65.8	16' [illegible]
" STBD 3 DP TK	17800	62.3	6' 6"
" ℄ 3 DB TK	3350	11.7	5' [illegible]
" PORT 4 TK	81[illegible]	28.6	14' 9"
" STBD 4 TK	7156	25.0	14' 9"
AFTER PEAK F.O.	2750	[illegible]9	6"
F.O. DAY TANK	4000	14.0	
LAZARETTE	22858	978	
HYDRAULIC OIL	[illegible]	27	69"
LUBE OIL	2000	[illegible]	675"

* NOTE: 100,000 GAL F.O. & 10,000 GAL F.W. WILL PUT TUG TO LOAD LINE MARK. TOTAL F.O. CAPACITY 140,000 GALS

SEA RACER CLASS

KLR 2-70
RD 8-71

-2-

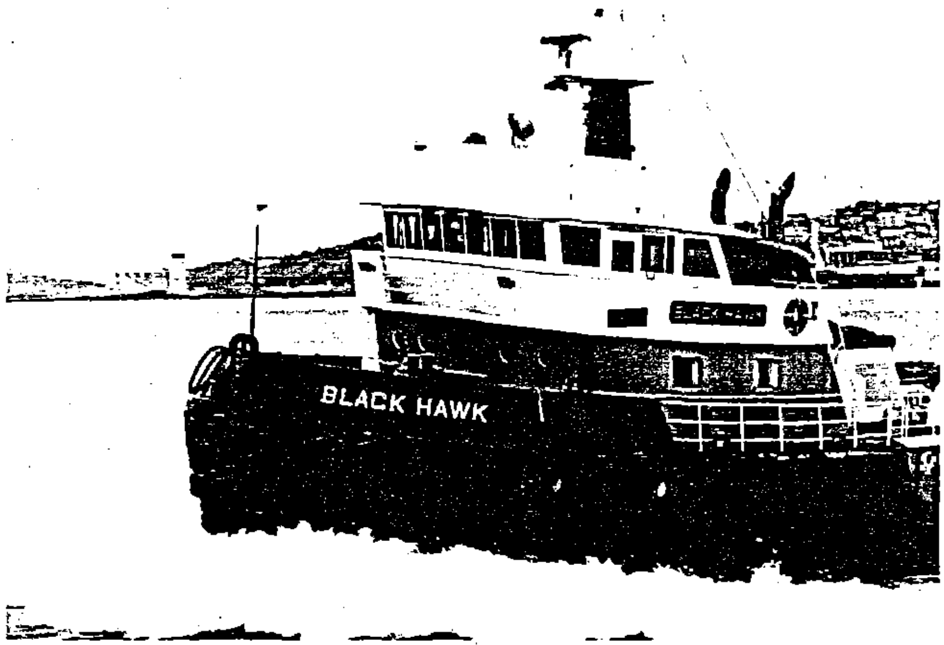
7/23/84

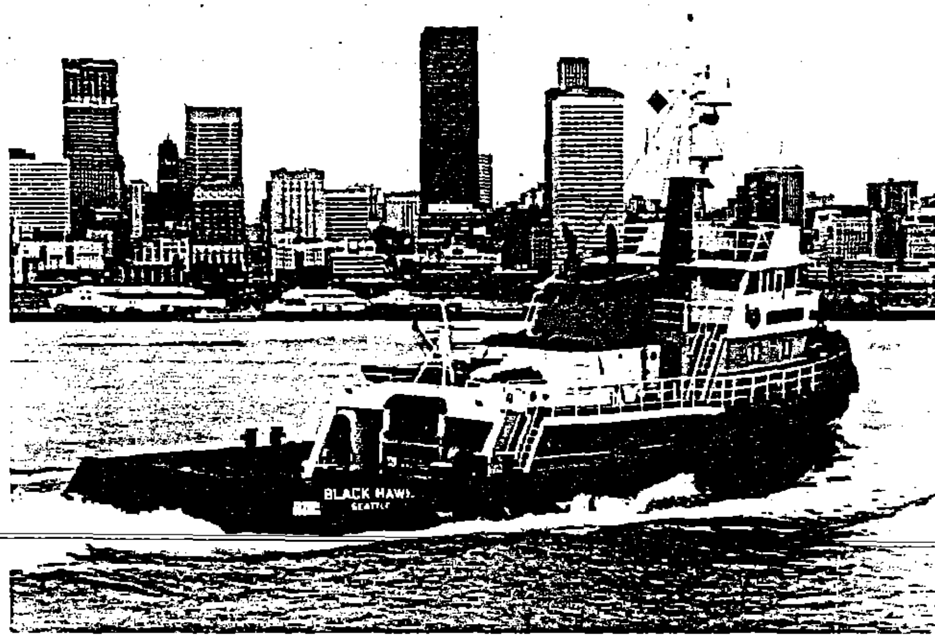
* OCEAN-GOING TUGS - use 23 lbs/BHP for Bollard Pull - fixed pitch

- at least 3-6 months job

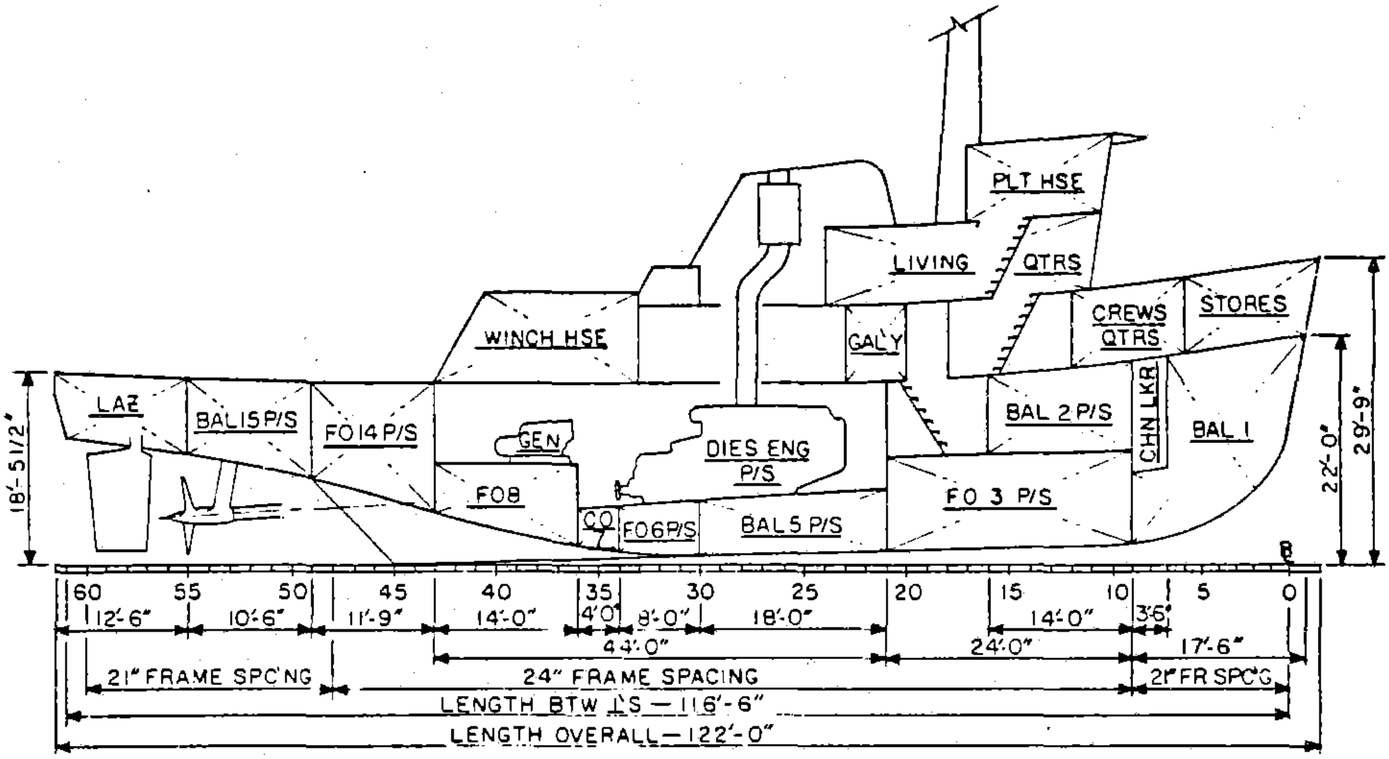
BLACKHAWK CLASS

APACHE 1968 - Alaska
BLACKHAWK 1968
SEMINOLE 1968 - cement barge

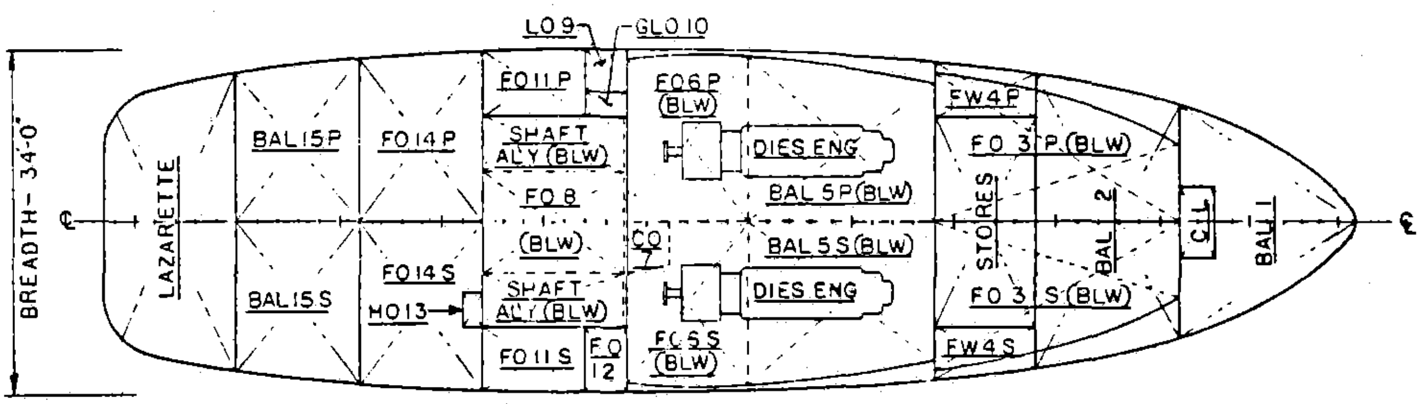




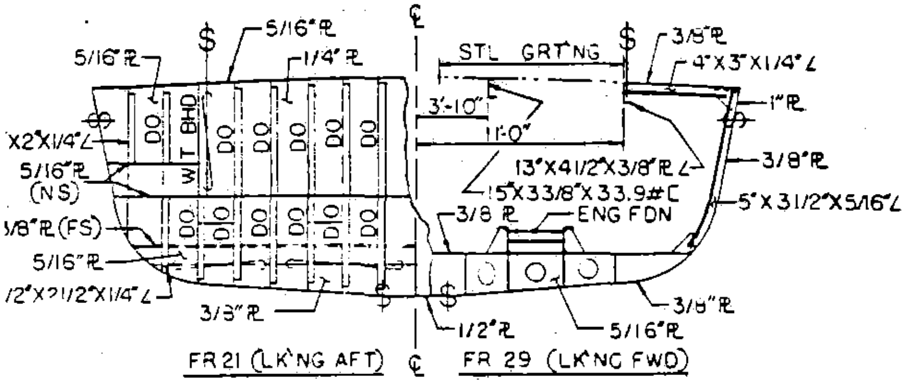
DIMENSIONS: 122′ x 34′ x 17′
ENGINES: (2) EMD 12-645-E2
HORSEPOWER: 3,300
FUEL: 103,000 gallons
LUBE: 1,400 gallons
WATER: 3,200 gallons
AUXILIARIES: (2) GM 6-71
(2) DELCO 115 KW, 450V, 60 HZ



INBOARD PROFILE



HOLD PLAN



MIDSHIP SECTION

TANK	GAL	CU FT	TANK	GAL	CU FT
BAL 1	12131	1622	FO 8	6737	900
" 2 P	8965	1199	LO 9	980	131
" 2 S	"	"	GEAR LO 10	450	60
FO 3 P	13618	1821	FO 11 P	5500	735
" 3 S	"	"	" 11 S	"	"
FW 4 P	2217	296	" 12	1400	187
" 4 S	"	"	HO 13	230	32
BAL 5 P	7967	1065	FO 14 P	13271	1774
" 5 S	"	"	" 14 S	13041	1742
FO 6 P	3618	484	BAL 15 P	7829	1047
" 6 S	3567	477	" 15 S	"	"
CO 7	533	71			

CROWLEY MARITIME

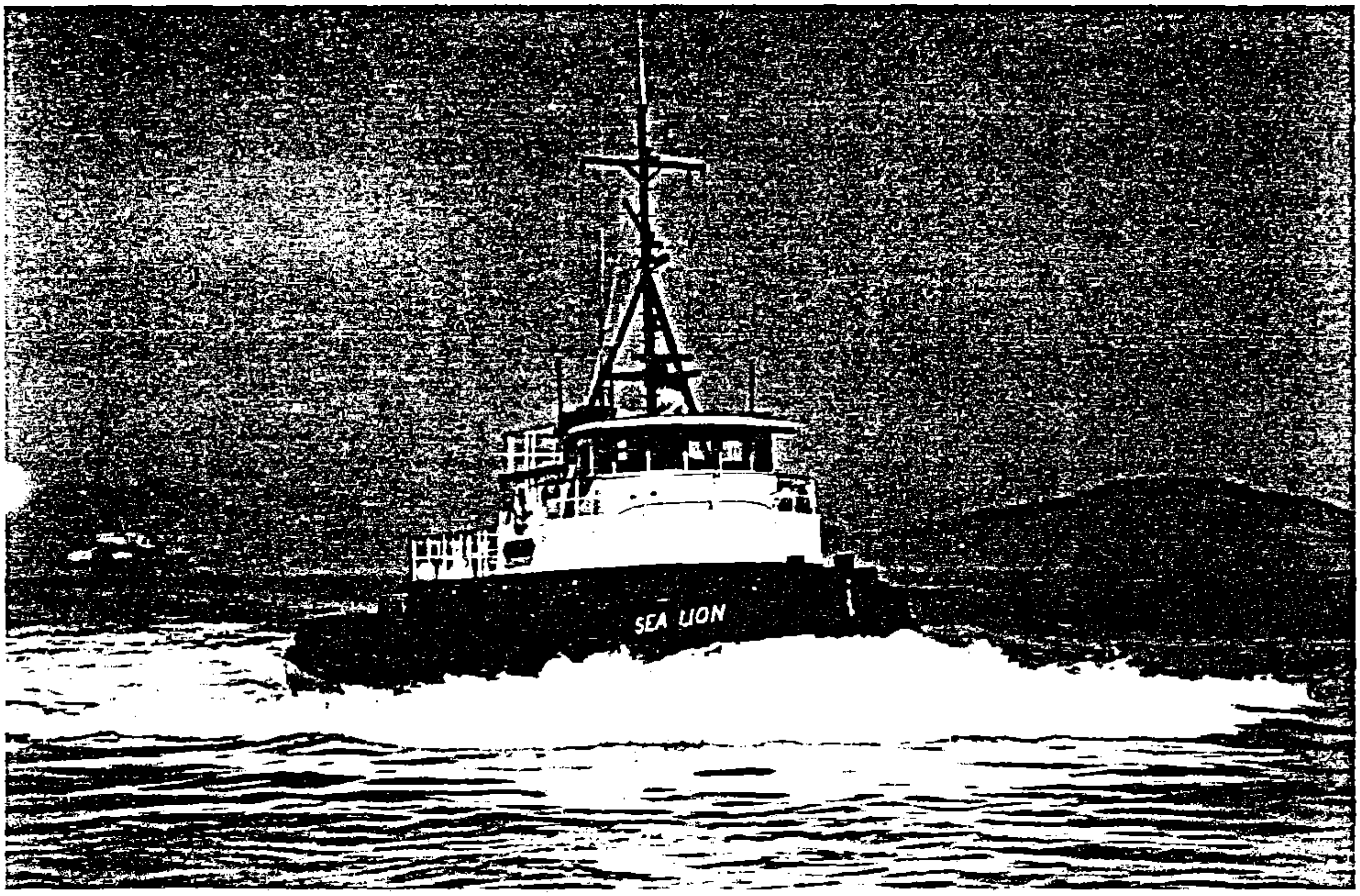
118 TWIN SCREW TUG
APACHE - BLACKHAWK
AND SEM[illegible]LE

*OCEAN-GOING
-w/ gears: <60 secs

DARING CLASS

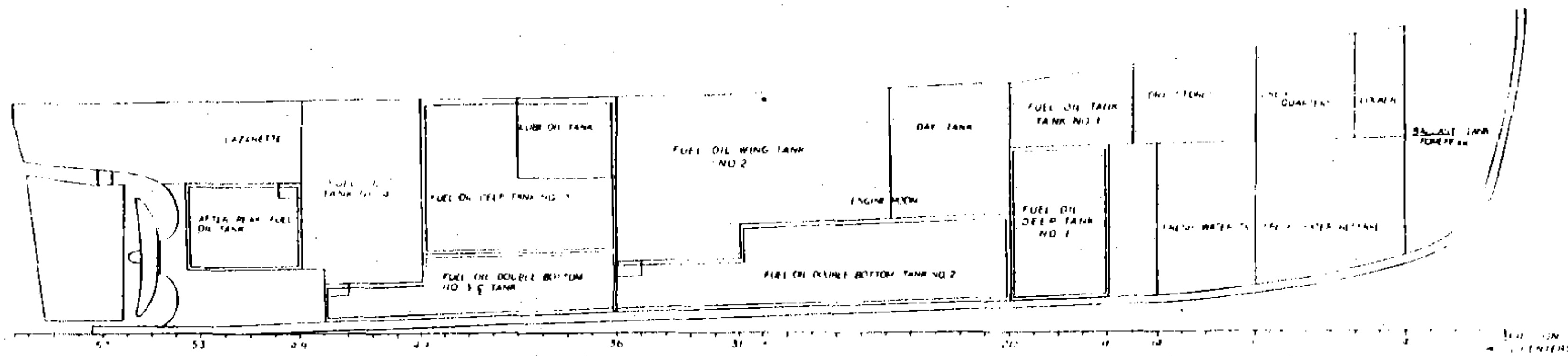
DARING	1965
SEA LION	1965
SEA WOLF	1965

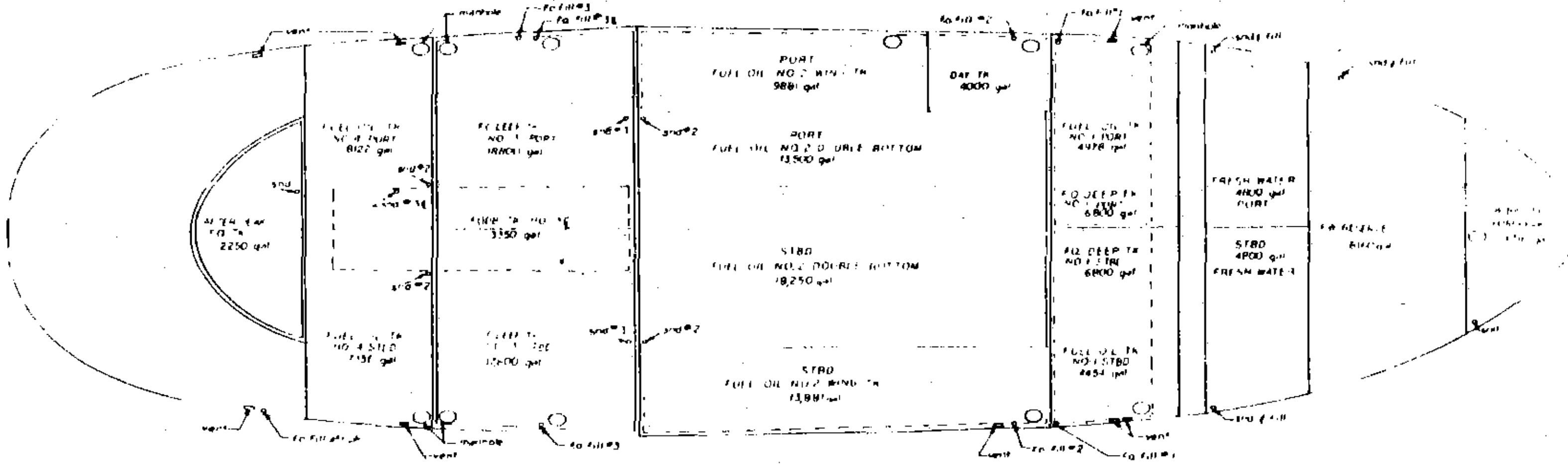
} 7 ships, actually

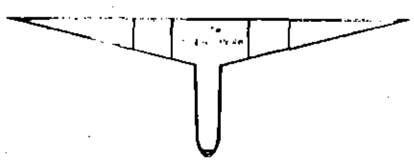


DIMENSIONS: 121′ x 32′ x 13′
ENGINE: EMD 16-567-D5 (1x?)
HORSEPOWER: 2,800
FUEL: 100,000 gallons

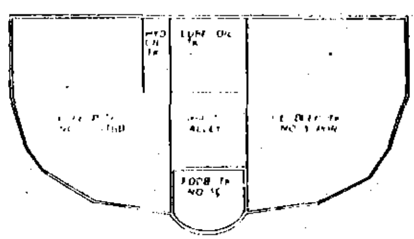
LUBE: 2,200 gallons
WATER: 18,000 gallons
AUXILIARIES: (2) CAT D-333
(2) 60KW, 120/208V



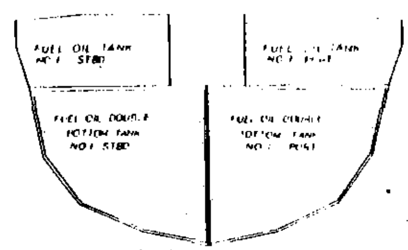




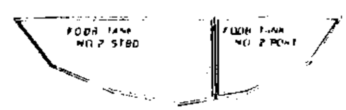
SECTION AT FRAME 49 LOOKING AFT



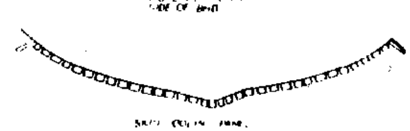
SECTION AT FRAME 36 LOOKING AFT

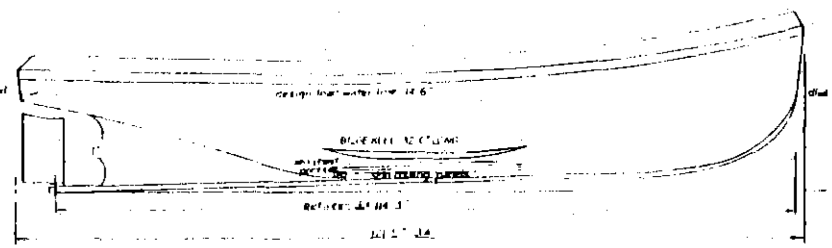


SECTION AT FRAME 19 LOOKING AFT



NO 2 F.O. TK-FAN
SIDE OF BHD





COMPARTMENT	CAPACITY GAL	TONNAGE	DEPTH
[illegible]	[illegible]	207	
FRESH WATER [illegible]	[illegible]	[illegible]	[illegible]
PORT	4800	[illegible]	[illegible]
STBD	4800		[illegible]
[illegible]	4976	[illegible]	[illegible]
[illegible] DP TK	6800	[illegible]	[illegible]
STBD	4454	[illegible]	[illegible]
[illegible] DP TK	[illegible]	[illegible]	6
PORT 2 WG TK	[illegible]	[illegible]	[illegible]
2 DB BT	[illegible]	[illegible]	[illegible]
STBD 2 WG TK	[illegible]	[illegible]	[illegible]
2 DB BT	[illegible]	[illegible]	[illegible]
PORT 3 DP TK	[illegible]	65.0	[illegible]
STBD 3 DP TK	[illegible]	[illegible]	[illegible]
C 3 DB TK	[illegible]	[illegible]	[illegible]
[illegible] 4 TK	[illegible]	[illegible]	[illegible]
STBD 4 TK	[illegible]	[illegible]	[illegible]
AFTER PEAK F.O.	[illegible]	[illegible]	[illegible]
F.O. DAY TANK	4000	140	
LAZARETTE	[illegible]	[illegible]	
HYDRAULIC OIL	85	[illegible]	[illegible]
LUBE OIL	2000	[illegible]	575

* NOTE [illegible]

Call Ian about Rates
Joe Keane
DTB
Honolulu

DILLINGHAM MARITIME PACIFIC DIVISION

DILLINGHAM TUG & BARGE CORPORATION

Sold

	MANA	MAMO II	MIKIALA II	MOANA HELE	MALANAE	MIKIOI	MIKIMIKI	MOANA HOLO
BUILT	1976	1977	1977	1977	1970	1967	1960	1977
BUILDER	MAIN IRON WORKS	MAIN IRON WORKS	MAIN IRON WORKS	MAIN IRON WORKS	ALBINA SHIPYARD	ALBINA SHIPYARD	ALBINA SHIPYARD	McDERMOTT S/Y
OFFICIAL NUMBER	571631	581354	585509	586628	524599	510653	281757	579119
ENGINES (SCREWS)	Two	Two	Two	Two	Two	Two	Two (single rudder)	Two
MODEL	EMD 12 645E6	Cat 399	Cat 399	Cat 399	FM 38D8-1/8	FM 38D8-1/8	FM 38D8-1/8	EMD 12 645E6
SHAFT HORSEPOWER	3,000	2,250	2,250	2,250	2,668	2,000	1,600	3,000
FUEL	105,000	66,000	66,000	66,000	80,000	65,000	55,000	115,000
POTABLE WATER-W.M.	22,000-No	2,100-Yes	2,100-Yes	2,100-Yes	5,340-Yes	5,700-No	5,700-No	2,100-Yes
DIMENSIONS (L/B/D)	123 x 34 x 16	98 x 32 x 11	98 x 32 x 11	98 x 32 x 11	113 x 32 x 14	106 x 28 x 13	106 x 28 x 13	120 x 34 x 14
CCF/TITLE XI FINANCED	Yes	CCF	CCF	TITLE XI	CCF	No	No	TITLE XI
WINCH	(2)2" x 2000'	(2)1-3/4"x1800'	(2)1-3/4"x1800'	(2)1-3/4"x1800'	(2)2" x 2000'	(2)1-3/4"x1800'	(2)1-3/4"x1800'	(2)2" x 2000'
MANUFACTURER	INTER-CON	MARKEY	MARKEY	MARKEY	MARKEY	TOKYO KIKAI	A. JOHNSON	MARKEY
BOW WINCH	No (CAP)	FOSS	FOSS	FOSS	No (CAP)	No (CAP)	No (CAP)	FOSS
KORT NOZZLES	Yes	No	No	No	No	No	No	No
GROSS TONS	109	125	125	125	285	243	239	198
NET BOOK VALUE (as of 12/31/82)								
CALL SIGN	WYH 6553	WYH 7483	WYH 7970	WYL 6361	WZU 7799	WY 2031	WM 7761	WYH 7274

NOTES:

1) Foss Launch & Tug Company owns tugs MAMO II and MOANA HELE.

2) Pacific Towboat & Salvage Company owns tug MIKIALA II.

/rhk
06.83
(Supersedes 04.83)

H

	NONI	MAHOE II	MI'OI	MEA'E	HUKI	~~MAKAALA II~~	MA'A	NOHA
BUILT	1968	1963	1980	1971	1970	1965	1973	1971
BUILDER	ALBINA SHIPYARD	ALBINA SHIPYARD	MAIN IRON WORKS	ALBINA SHIPYARD	ALBINA SHIPYARD	ALBINA SHIPYARD	BREAUX BAY CRAFT	BREAUX BAY CRAFT
OFFICIAL NUMBER	515166	293284	629266	530653	524598	501133	552420	537094
ENGINES (SCREWS)	Two C.P.	Two	Two F.R.	Two	Two	One	Two	Two
MODEL	Cat 398	Cat 398	Cat 398	Cat 398	Cat 379	Cat 398A	GM 8V-71	GM 8V-71
SHAFT HORSEPOWER	1,700	1,700	1,700	1,700	1,430	850	680	492
FUEL	18,000	18,000	26,000	32,500	10,715	5,714	1,000	412
POTABLE WATER-W.M.	1,000-No	1,000-No	3,000-Yes	1,147-No	80	150	300	50
DIMENSIONS (L/B/D)	76' x 22' x 11'	76' x 22' x 11'	76' x 26' x 11'	80' x 25' x 9'	60' x 20' x 9'	60' x 17' x 7'	46' x 16' x 6'	41' x 14' x 6'
CCF FINANCED	No	No	Yes	Yes	Yes	No	Yes	No
WINCH	(1)1-5/8"x1700'	(1)1-5/8"x1700'	(1)1-5/8"x1700'	(1)1-5/8"x1700'	No	No	No	No
MANUFACTURER	FUKUSHIMA	Not Identifiable	MARKEY	A. JOHNSON	-	-	-	-
BOW WINCH	No (CAP)	No (CAP)	FOSS	FOSS	No	No	No	No
KORT NOZZLES	No	No	Yes	No	No	No	No	No
GROSS TONS	99	98	106	98	77	58	29	24
CERT. PASSENGER/CARGO	-	-	-	-	-	-	Yes	Yes
NET BOOK VALUE (as of 12/31/82)								
CALL SIGN	WZZ 2579	WO 8120	WYR 3932	WYZ 3237	WZU 7800	WU 9930	WZF 8494	WYZ 6155

NOTE:

Foss Launch & Tug Company owns tugs MI'OI and MEA'E.

Dunk
2/21/84

/rhk
06.83
(Supersedes 04.83)

	DTB-27	DTB-29	DTB-35	DTB-39	DTB-40*	DTB-42	DTB-43
BUILT	1966	1968	1971	1967	1977	1970	1957
BUILDER	ALBINA SHIPYARD	DSY (Honolulu)	ALBINA SHIPYARD	TODD SHIPYARD	WEST GULF MARINE	TODD SHIPYARD	TODD SHIPYARD
OFFICIAL NUMBER	503956	515819	536669	507342	585935	525880	274325
TYPE	Deck	Deck/House	Deck	Deck/House	Deck/House	Tank	Tank
CAPACITY	1,500 s/t	2,000 s/t	1,800 s/t	4,200 s/t	7,100 s/t	43,000 bbls.	10,000 bbls.
DIMENSIONS (L/B/D)	180' x 45' x 11'	193' x 51' x 13'	196' x 45' x 12'	240' x 60' x 16'	286' x 76' x 17'	250' x 76' x 16'	170' x 44' x 12'
USABLE DECK SPACE	165' x 40'	178' x 47'	181' x 40'	219' x 55'	261' x 69'	-	-
LIGHT DRAFT	2' 6"	3'	3'	2' 7-5/8"	1' 3-1/2"	1' 6"	1'
DEEP DRAFT	8' 9-3/4"	9' 7"	9' 6-3/8"	12' 11-3/4"	14' 4"	13' 8-1/2"	9' 9-3/4"
GROSS TONS	768	1,119	841	2,061	3,202	2,654	811
REMARKS	6-ft. Stanchion Fence.	House 84' x 17'; 6-ft. Enclosed Timber Fence.	6-ft. Enclosed Steel Fence.	House 88' x 20'; 8-ft. Enclosed Timber Fence; Stern Rake Ballast System.	Stanchion Fence; Ballast System; House.	Black/Clean Oil Products.	Black Oil Products.
NET BOOK VALUE (as of 12/31/82)							

-oOo-

*TITLE XI Financed.

rhk
6.83
(Supersedes 04.83)

Dillingham Inter-Office Correspondence

TO: FILE
DATE: NOV. 7, 1983
FROM: IAN SANDISON
INITIAL: [handwritten initials]
SUBJECT: BOLLARD PULL TEST OF TUGS, MANA & MALANAE
REFERENCE:

Test Dates:	Three separate tests of the MANA's bollard pull were made on April 9, October 20, and October 25, 1983. The MALANAE was also tested on October 25.
Instruments Used:	A Dillon dynamometer was used on April 9. The OTEC-1 tension link was used on October 20. A Martin Decker tensiometer and the Navy calibrated ram tensioner were used on October 25.
Results:	The MANA's maximum measured bollard pull was 73,000 lbs. - at this point the winch slipped. It is calculated that the MANA could pull between 85,000 and 90,000 lbs. with the winch dogged. The MALANAE's maximum pull is approximately 60,000 lbs. - the winch did not slip.
Correction of Measured Data:	The data from the Dillon dynamometer, ram tensioner, and the OTEC-1 tension link, all agreed with one another. The Martin Decker tensiometer read consistently higher than the other instruments. Its data has been calibrated to the other instruments to determine the MALANAE's bollard pull.

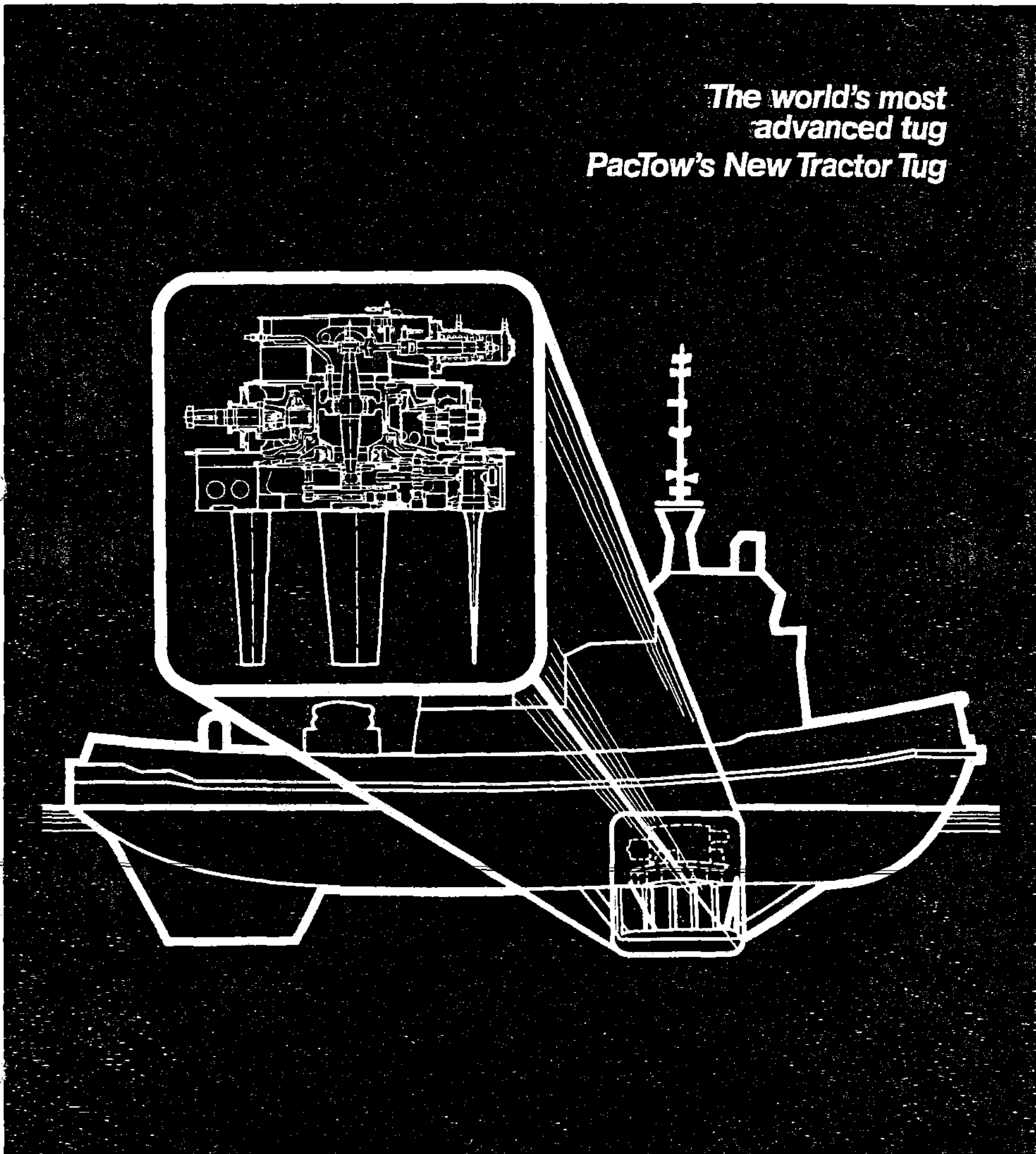
The data from each test is attached along with two graphical presentations of the data.

IS:jfk
Attachments

cc: Jim Prentice
Terry White (DTB)
MALANAE
MANA
Joe Keane (DTB)

PacTow

SETS THE STANDARD



UNMATCHED MANEUVERABILITY AND SAFETY

Pacific Towboat now offers the ultimate in tugboat capabilities and performance with the introduction of its fleet's newest and most exciting addition—the PacTow Tractor Tug.

The PacTow Tractor Tug is faster, safer, more powerful and more economical than conventional tugboats. It is also able to maneuver in ship assist situations as no other tug can.

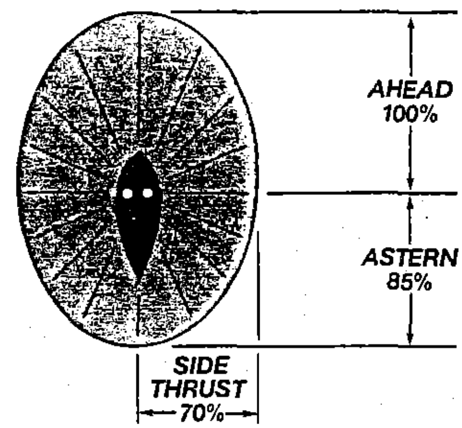
Because of its unique cycloidal propulsion system, this "state of the art" tug is able to produce thrust in any desired direction without changing its positional heading or loosing power. The revolutionary system allows the tug to offer maximum responsiveness, efficiency and safety in all tanker escort and vessel assist operations.

The tractor tug offers potential savings in reduced docking and undocking time. Due to the tug's responsiveness and maneuverability, pilots are able to escort very large vessels in and out of tight berths without the added time allowances required by other tug models. This rapid transit ability can decrease assist time by as much as 20%, resulting in further cost savings to shipping companies.

Other advantages include significant reductions in the risk of capsizing tugboats. Tractor tug operator reaction time is increased so that pilots may better adjust to changes in weather, sea or harbor conditions, thusly avoiding accidents.

In many harbor and waterway situations, one tractor tug may suffice where two conventional tugs are needed or a job which previously required three conventional tugs can now be expertly completed by two PacTow Tractor Tugs—with a minimum amount of time and maximum amount of safety.

FULL POWER WHEREVER IT IS NEEDED 3500 HP



THRUST VECTOR DIAGRAM

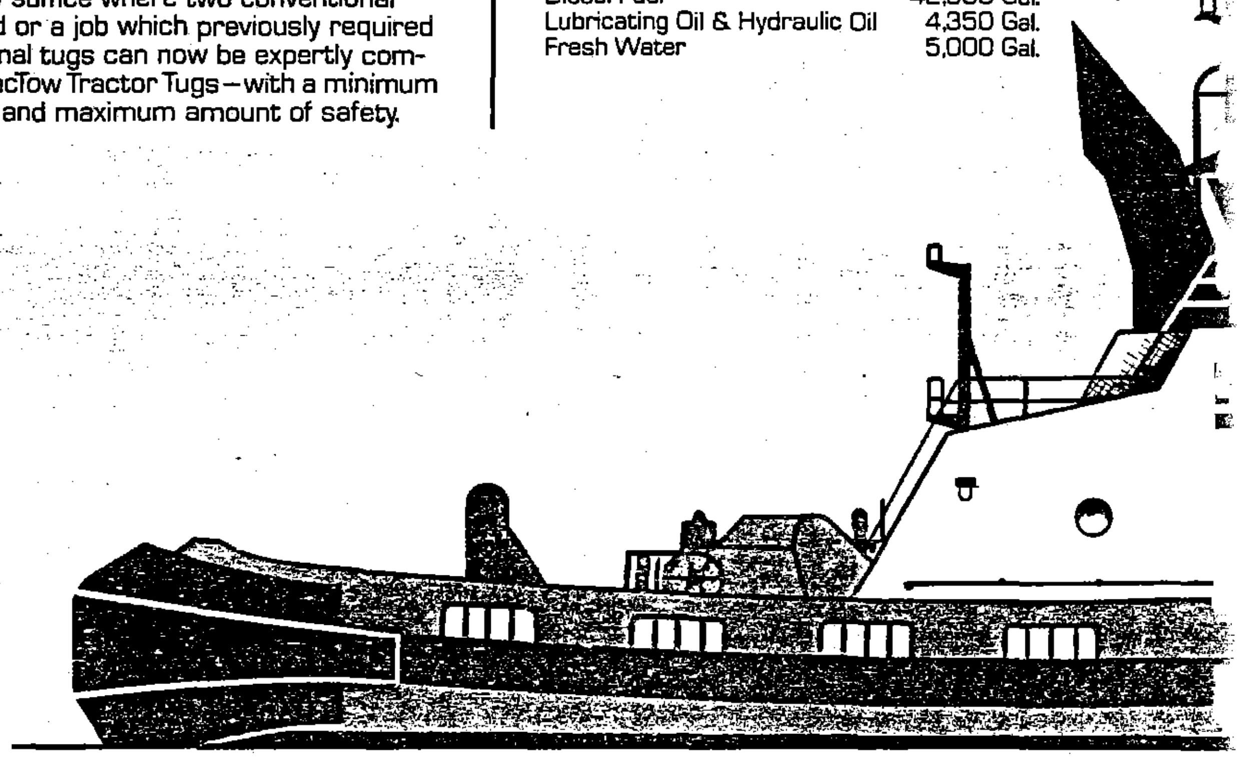
Length Overall, Hull Molded	100'0"
Length on Design Waterline	96'-0"
Breadth, Main Deck, Molded	36'-0"
Depth, Keel, Amidships	13'-0"
Gross Tonnage	195
Power, Total Maximum Continuous BHP	3,500
Complement, Officers and Crew	6

Design Waterline Characteristics:

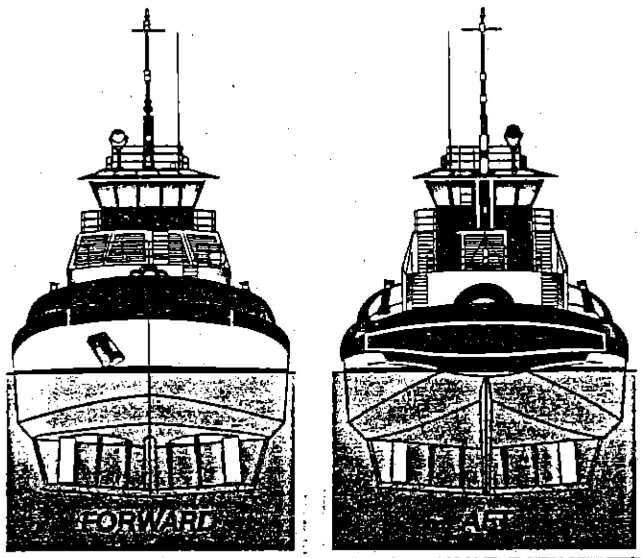
Displacement Design Load Waterline	540 LT.
Draft, Amidships Design Waterline	16'-2"

Maximum Capacities:

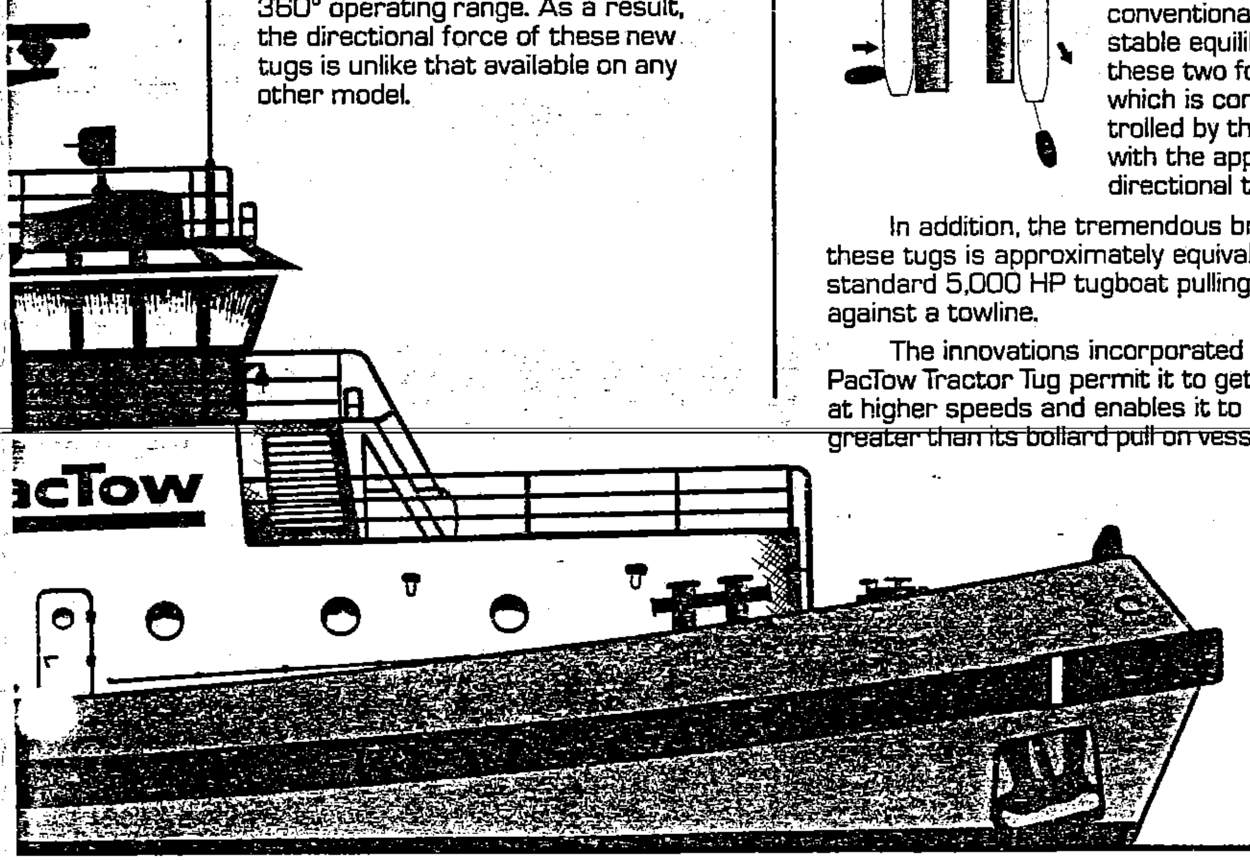
Diesel Fuel	42,500 Gal.
Lubricating Oil & Hydraulic Oil	4,350 Gal.
Fresh Water	5,000 Gal.



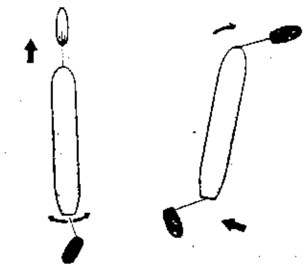
THE REVOLUTIONARY CYCLOIDAL PROPULSION SYSTEM



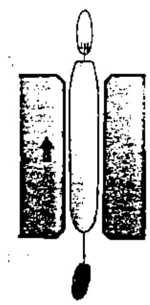
The cycloidal propeller is a vertically-oriented controllable pitch propulsion system with propeller blades located on the periphery of a rotor. The movement and angle of the rotor blades is variably controlled to produce both the propulsion and steering forces through a stepless 360° operating range. As a result, the directional force of these new tugs is unlike that available on any other model.



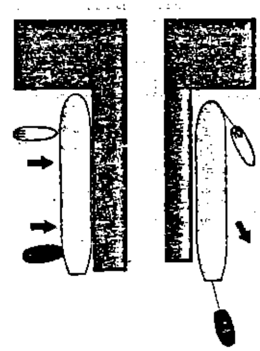
MORE TUG POWER SAVES TIME AND MONEY



The tractor tug vessel configuation is essentially different from the configuration of other tugboats. While offering 360° horizontal and overhead visibility, its principal purpose is as a ship assist vessel.



The tugs can immediately produce thrust in any desired direction, depending upon the requirements of the situation. They can proceed forward or backward without having to reverse the engine during maneuvers. They can also go sideward, can be brought to a complete stop while going full ahead within a distance of approximately their own length, and can turn in a circle of not more than their length.



The tractor tug is designed so that the towline forces act about the pivot point on the tug, while the propeller thrust acts ahead of the pivot point. Unlike a conventional tug, there is a stable equilibrium between these two force points which is continually controlled by the tug operator with the application of directional thrust.

In addition, the tremendous braking power of these tugs is approximately equivalent to that of a standard 5,000 HP tugboat pulling at full speed against a towline.

The innovations incorporated within the PacTow Tractor Tug permit it to get alongside ships at higher speeds and enables it to exert forces greater than its bollard pull on vessels it is assisting.

SOUTHERN CALIFORNIA
SHIP ASSIST FLEET

Los Angeles/Long Beach					
Vessel	**H.P.**	**Engine(s)**	**Special Features**		
Peter Foss	3150	CatD399	Twin Screw	Kort Nozzle	
Iver Foss	3000	CatD399	Twin Screw	Kort Nozzle	
Pacific Titan	3000	CatD399	Twin Screw		
Pacific Viking	3000	CatD399	Twin Screw		
Pacific King	2550	CatD398	Twin Screw	Kort Nozzle	Flanking Rudder
Pacific Queen	2550	CatD398	Twin Screw	Kort Nozzle	Flanking Rudder
Pacific Knight	2550	CatD398	Twin Screw	Kort Nozzle	Flanking Rudder
Pacific Tractor	3500	EMD12645E6	Voith Schneider Cycloidal Propulsion		
Pacific Escort	3500	EMD12645E6	Voith Schneider Cycloidal Propulsion		

San Diego					
Vessel	**H.P.**	**Engine(s)**	**Special Features**		
Pacific Mariner	3000	CatD399	Twin Screw		
Pacific Saturn	2400	CatD398	Twin Screw		
Palomar	2400	CatD398	Twin Screw		
San Jacinto	1000	Cat348	Single Screw		

Port Hueneme					
Vessel	**H.P.**	**Engine(s)**	**Special Features**		
Cuyamaca	1500	Cat379B	Twin Screw		
Pacific Gemini	2000	Cat348	Twin Screw		

COMPLETE HARBOR SERVICES

Bunker Barging
Potable Water Barging
Cargo Transport
Ship Stores
Water Taxi

PacTow
A Dillingham Maritime Company

Los Angeles/Long Beach
Pier D, Berth 35
Long Beach, CA 90802
(213) 435-0171

San Diego
1839 Water Street
San Diego, CA 92113
(714) 234-8228

Port Hueneme
(213) 432-6487

FAUSTUG

Pier 15, The Embarcadero, Second Floor, San Francisco, CA 94111
Telephone (415) 986-1050, Telex 172495—Faustug SFO

July 30, 1984

Mr. Johannes Hoech
Luis Vega and Associates
2550 9th St. Suite 205
Berkeley, CA 94710

Dear Mr. Hoech:

Our tractor tugs are the ideal vessels to suppport the Hawaii cable laying project you described. As I understand the project, you need tugs to position, supply, and precisely maneuver a large barge operating between Hawaiian islands. Our tugs have performed similar work supporting the construction of the sewage outfall at Monterey, positioning a large pipe-laying barge and resupplying the project with gravel barges, fuel, and crew.

The enclosed excerpt from a proposal to build tugs similar to ours for the U.S. Navy should contain all the technical information and comparisons you need. Bear in mind that the Navy was looking for harbor tugs; our existing tugs are built for coastal and offshore work as well. We have successfully towed barges from South Carolina through the Panama Canal to California and from Seattle to Alaska. None of the other tractor tugs operating now in the U.S. have this capability.

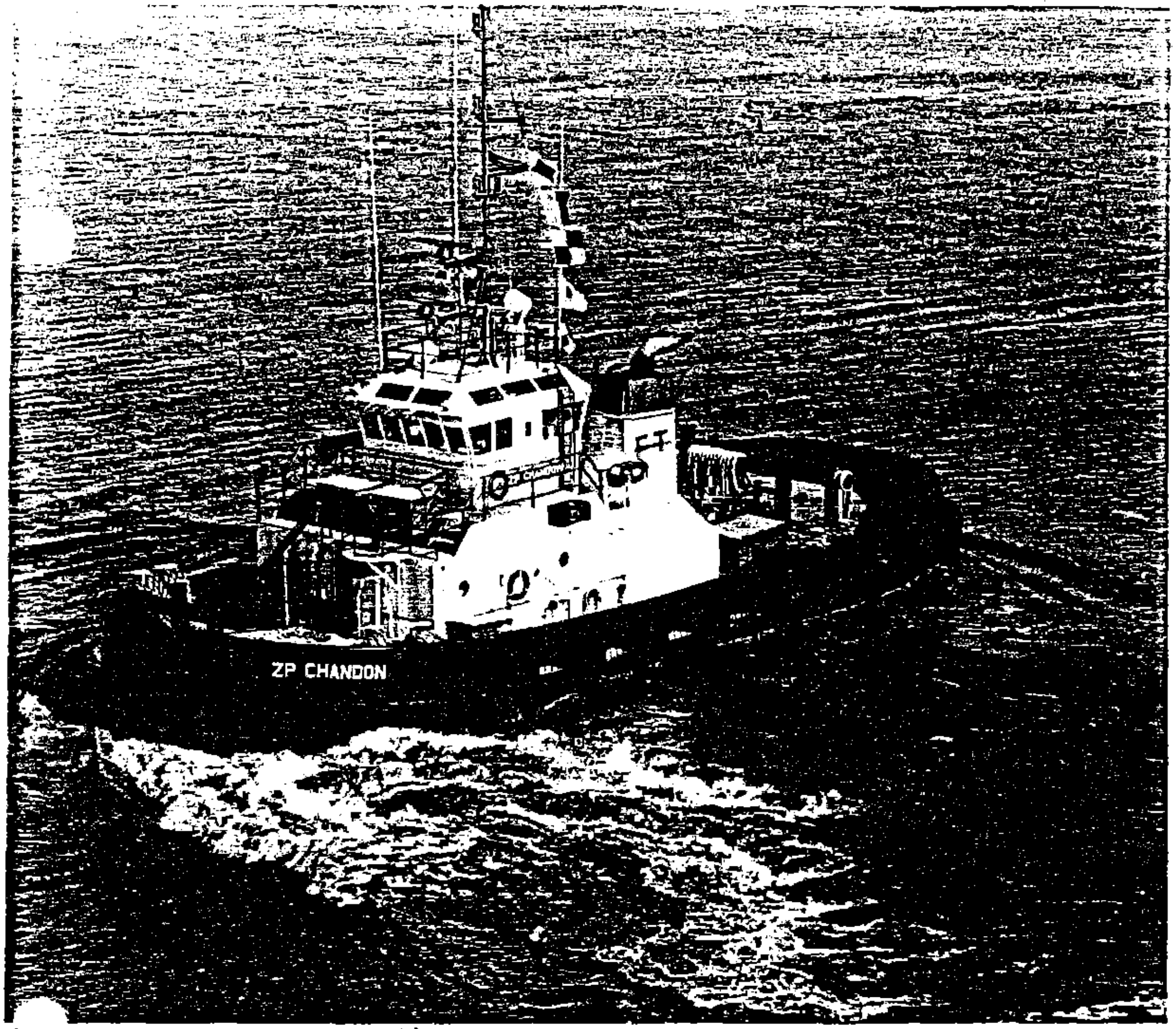
Our existing tugs also employ fuel-efficient turbocharged four stroke engines capable of burning cheaper residual fuel in addition to diesel oil.

At this stage of the project, we are not prepared to make price quotations, other than to say that our time charter rates are competitive with less capable conventional tugs. My guess is that owning and operating tugs will probably not be cost effective for one project, unless it spans several years; however, we will be happy to quote a price for an existing tug or a newbuilding in response to a serious inquiry.

Please call if you have any questions. We could arrange for you to observe a tug in action first-hand, if you would like.

Very truly yours,

Louis Cohen
Chartering Manager



TRACTOR TUG *ZP CHANDON* demonstrates ability to complete 360° turn in 9 seconds. The tug will also reverse from full ahead speed of 12.4 kt in under 10 seconds and generates 52 tons of bollard thrust.

Faustug's remarkable tractor tugs

The tugs are powered with two Kort nozzles located about one-third of the length back from the bow. This enables them to turn 360 degrees in 9 seconds, reverse from full ahead at 12.4 knots to astern motion in 10 seconds and to exert 70 percent thrust at right angles from the direction of the bow.

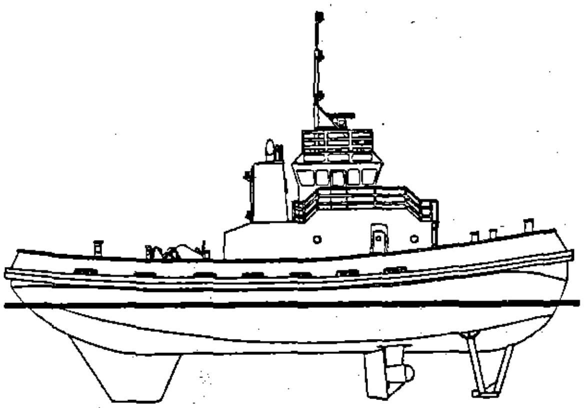
Capt. Thomas J. Faust, President,
Faustug Marine Corp.

FAUSTUG MARINE introduced the first fleet of tractor tugs (designated Tractugs) into the Gulf of Mexico and Pacific Coast in December 1981. Since then the tugs have performed virtually every conceivable task. Practically the only limitation on their versatility is that of water depth. The tug's twin Kort nozzles are located one-third of the vessel's length back from the bow and extend 16 ft below the waterline. This depth is advantageous in maintaining full thrusting power at all times and avoiding cavitation. During their first year of operation our tractugs have done everything from 6,000-mile tows to ship-assist and precision rig and barge maneuvering.

Design. Our original intention was to build a flexible and commercial boat that could get the job done. All the conceptual engineering and working drawings were prepared by Design Associates of New Orleans. The vessels in our fleet were built by Valley Shipbuilding, Inc., of Brownsville, Texas, our wholly owned shipbuilding facility. Seven vessels are currently in the water and the eighth vessel will be launched in another month. Three different designs give greater flexibility and enhance fleet utilization.

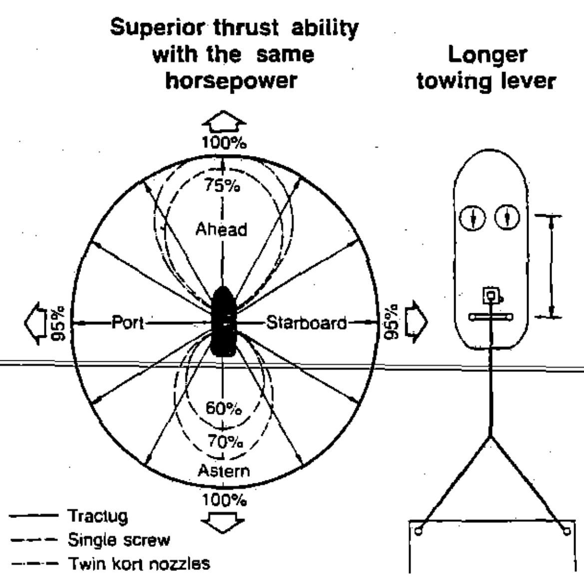
We classify them as the Diesel Tractug, the Heavy Fuel Tractug and the Wide Body/Extended Range Tractug. Our Heavy Fuel and Wide-Body boats use

SPECIFICATIONS
ZP CAYMUS, ZP CARNEROS, ZP MAYACAMAS, ZP CHANDON, ZP ACACIA, ZP MONTELENA

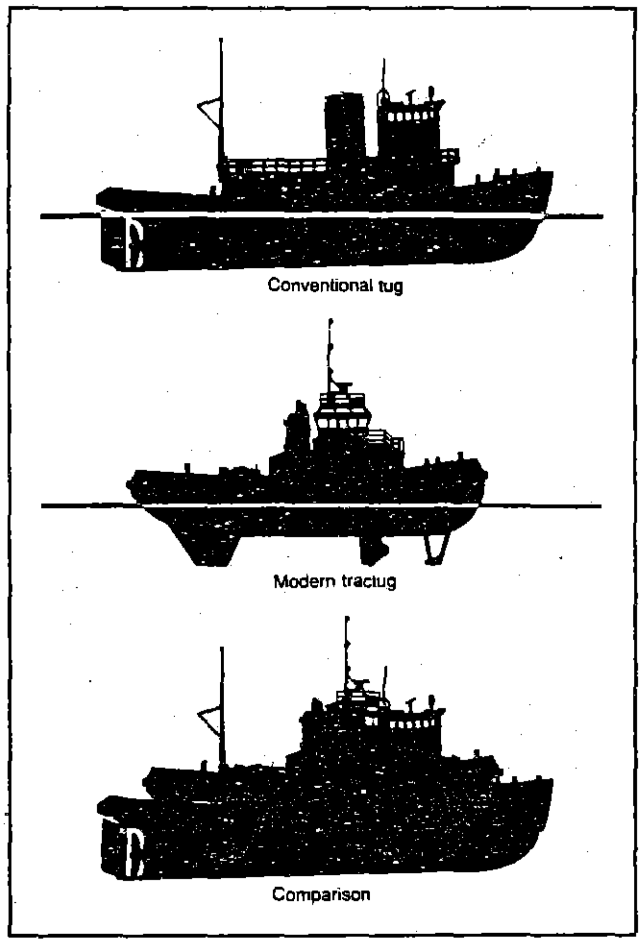


	EMD TRACTUG	HEAVY FUEL TRACTUG	WIDE BODY TRACTUG
LENGTH	93'	93'	93'
WIDTH	34'	34'	38'
DRAFT	18'	16'	16'
ENGINES	EMD	M.A.N.-B&W	M.A.N.-B&W
RATING	4,000 SHP	4,200 SHP	4,200 SHP
BOLLARD THRUST	45 TONS	52 TONS	52 TONS
CRUISING RANGE UNDER TOW	2,400 MI	2,400 MI	3,900 MI

THREE ENGINE/HULL COMBINATIONS give flexibility to send the right vessel for the job. Wide body tractug also burns heavy fuel.



LONGER TOWING LEVER and ability to apply powerful thrust through 360° azimuth are responsible for tractug's towing advantages.



PROFILE OVERLAY SHOWS propeller placement, draft and size of tractug compared to conventional vessel.

intermediate IF 180 fuel.

We designed the vessels to be simple to manufacture and assemble at the shipyard and easy to service and maintain. We also sought to standardize equipment and appearance and to ensure ease of operation and low crew manning scale.

The single chine hull is built to full ABS A-1 Ocean Towing loadline standards. In accord with 1984 SOLAS standards, a double hull surrounds the engine room to help prevent sinking if the vessel is rammed. The superstructure is flared inward so as not to interfere with the tow she is towing. Tractug is basically a simple vessel to manufacture. All major components are manufactured in controlled offsite factories. Final assembly takes place in a shipyard, preferably one with deep water access.

Development of the tractor tug. The first tractor tug, invented in Germany in 1944, featured a revolutionary cycloidal propeller, similar to an inverted helicopter blade, which gave excellent maneuverability but very poor fuel and power efficiency. An experimental design of the early 50s proved that when placed one-third back from the bow the propellers increased vessel maneuverability.

For the next 20 years, about 150 tractor tugs were added to the worldwide fleet. In 1967, the first steera-

TABLE 1—Tugboat thrust

Propulsion Type	Bollard Pull/HP Ahead	Astern	Side
Twin screw w/open props	25.9	19.4	0
Twin screw w/open props & flank rudder	25.8	19.1	0
Twin screw w/conventional nozzles	33.6	18.0	0
Twin screw/spec nozzles & flank rudder	29.7	27.2	0
Water tractor twin prop z drive	33.6	33.6	33.6
Water tractor twin cycloidal	24.9	23.7	23.7

ble right-angle drive was perfected and installed on the tug *Janus*, producing 30 percent more bollard thrust for the same installed engine brake horsepower using a steerable Kort nozzle. In 1972, the first ocean-going tractor tug was built. Since 1972, almost 400 additional tractor tugs have been built. The lion's share of these, particularly those delivered in the past three years, have the improved steerable right-angle drive units similar to the ones discussed here.

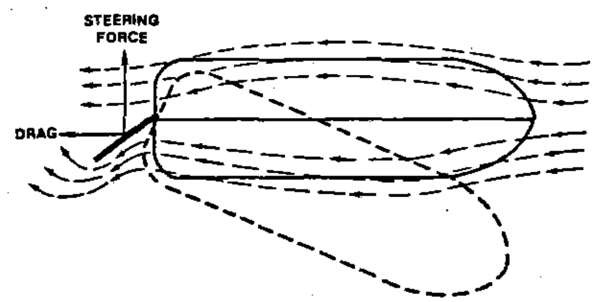
Silhouette overlays contrast the conventional tug with the tractor tug. The tractor tug isn't any deeper than the conventional tug, but its propellers are deeper below the waterline and forward on the tug rather than at the stern. The location of the propeller and the type used contribute to the performance of the vessel.

We selected the right-angle, or Z-Peller, drive type because it gives the most powerful performance. As shown in Table 1, the Kort nozzle application has superior performance capability over open wheel or cycloidal type propeller.

Thrust and performance. The power from a Kort nozzle is the same whether installed in tractor or in conventional configuration. An additional benefit of installing the wheel in tractor configuration is the non-interference of the hull with the incoming water flow. The continuous water flow at this level allows the vessel to develop better thrust without the hindrance of cavitation.

Table 2 contrasts the effectiveness of different propulsion types. As long as the headway of the ship or tow is about zero, all methods are fairly effective. But, as the speed of the tow increases, the effectiveness of the fixed thrust rapidly diminishes.

TABLE 2—Thrust and headway



TONS OF THRUST AS A FUNCTION OF HEADWAY

SHIP HEADWAY (KNOTS)	1000 hp BOW THRUSTER	4200 hp CONVENTIONAL TUG AT BOW	4200 hp TRACTUG AT BOW
0	6.9	48.0	48.0
3	3.5	23.4	48.0
4	2.9	23.0	48.0
7	1.7	21.5	48.0
10	1.5	18.3	48.0

The relative values presented here are extrapolated from studies performed by Dr. Ian Dand of the Royal Hydrodynamics facility in London. Static bollard thrust or pull is only a passing relationship when compared to dynamic bollard pull in difficult sea conditions. The conventional tug often has to use a lot of rudder to try and maintain position. The more rudder angle used, the less her ability to control the tow; the greater the water current the tow fights, the less effective is the thrust that is available for the tow. The design configuration of the tractug maximizes thrust control. The tractor has a 360-degree uninterrupted arc with which to sweep her thrust.

Seakeeping ability is another aspect where the tractug excels. Seakeeping is the ability of the vessel to make controlled headway in difficult circumstances. A tractug under tow in a moderate sea is analogous to a cork. That is, the vessel rides up on the swells and rides down. She doesn't pitch or pound. The pull is constant and without propeller cavitation.

How it works. The tractug has 360 degrees of thrust capability versus only fore and aft thrust capability with the conventional tug. The tractor tug also is capable of applying 70 percent thrust to each side directly perpendicular to the direction in which the bow is pointed. The 360 degrees of thrust capability coupled with a larger towing lever enables the tractug to always be in the best towing position and to avert dangerous situations. A towing lever approximately seven times greater than the conventional tug's enables a tractor tug to make precision towing with greater safety.

A fin installed beneath the lower aft part on the tractug shifts the center of gravity of the underwater lateral plane towards the stern to increase the effective lever between the thrust and the turning center of the vessel. It also improves the tractug's course stability. With the stern driven conventional screw tug, the main forces—towrope pull and screw propeller thrust—are in unstable equilibrium because the towrope pull acts ahead of the total forces formed by rudder force and thrust. Today's modern tractor tug enhances stability by ensuring that the propeller thrust and the steering force act ahead of the point of attack of towrope pull.

The maneuvering capability of the tractugs is impressive. They can go from full ahead at 12.4 knots to astern motion in less than 10 seconds. The response time to a 360 degree turn is 9 seconds, versus a much longer time for the conventional tug. With joy stick controls to simplify matters, it's possible to train a complete novice to be an expert in less than 60 hours at the throttle.

Today's modern tractor tugs are reliable. We have designed our tractor tugs to the highest standards set by the regulatory boards. Our tractor tugs are the first vessels under 200-ton class to be registered as ACCU vessels. This means that full engine room monitors and controls are located on the bridge. It makes sense for the captain to be aware of the condition of the machinery at all times.

Bottom line. Last, but not least important, are cost factors. We've equipped our tractor tug with a heavy fuel engine. Heavy fuel engines have been used for some time in stationary shoreside power plants or on ships as auxiliary generators. Our application is the first time heavy fuel engines have been used as a prime mover in tugs under 200 tons. The result of the application is still under study. While no clear answers are available yet, our system has the capability of burning straight heavy fuel under a myriad of conditions and down to twenty percent load. Now the difference between heavy fuel and diesel prices is painfully distinct. In Charleston, the posted price of diesel is $308 a metric ton. The posted price of IF 180 is $177. The saving is $131 a metric ton. Our engines can deliver under heavy fuel conditions. The heavy fuel tractug has the fuel economics of a 2,400 hp conventional diesel-burning tug.—*CMc*

A complete and basic change in tug boat design

TUG

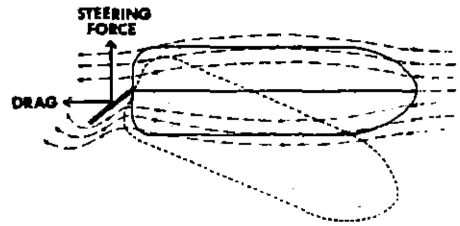
The conventional tug's slow response and poor maneuverability are the result of a 145 year old design deficiency. It's a matter of basic physics. The rudder produces drag and loss of power. A conventional tug with its rudder at 20 degrees has lost half its thrust. If she is underway, the loss is even greater. A second propeller, nozzles or a larger rudder can't overcome the disadvantages of pushing and steering a tug from its extreme after end. A bow thruster is a costly and inefficient compromise since it has little effect at speeds over 3 knots.

TRACTOR TUG

The tractor tug design was developed in Europe over 30 years ago to solve the maneuvering problems of the conventional tug. More than 600 are now in operation throughout the world. It has proven its worth offshore in the North Sea and handling ships at Rotterdam, the world's busiest port.

TRACTUG

Faustug Marine's Tractug draws on this tradition with several innovations of its own. It is designed to be pulled through the water by its propulsion system. Tractug's twin propeller nozzles are placed forward, a third the distance from the bow, and they can rotate 360 degrees to maneuver and apply full power in any direction without rudder drag. Protected by a guard strut, the steerable propellers are mounted eight feet deeper than the conventional tug's and pull more effectively from the calm water at this level without interference or cavitation. The entire system is controlled by a single lever.



TONS OF THRUST AS A FUNCTION OF HEADWAY

Ship Headway (knots)	1000 hp Bow Thruster	4200 hp Conventional Tug at bow	4200 hp Tractug at bow
0	6.9	48.0	48.0
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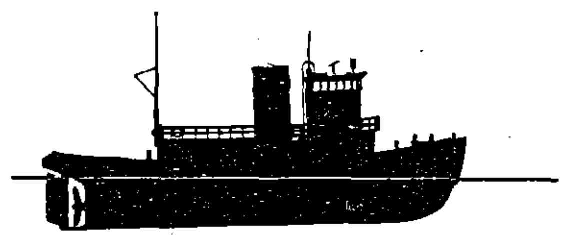
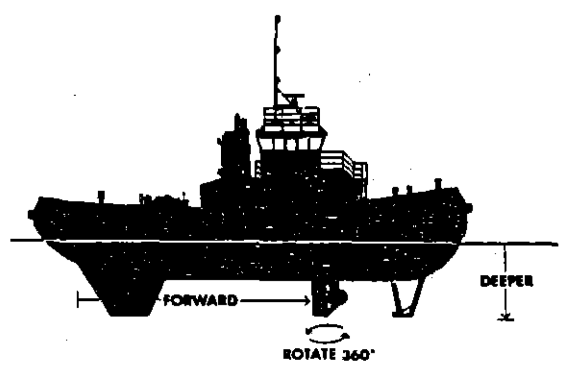


CONVENTIONAL TUG

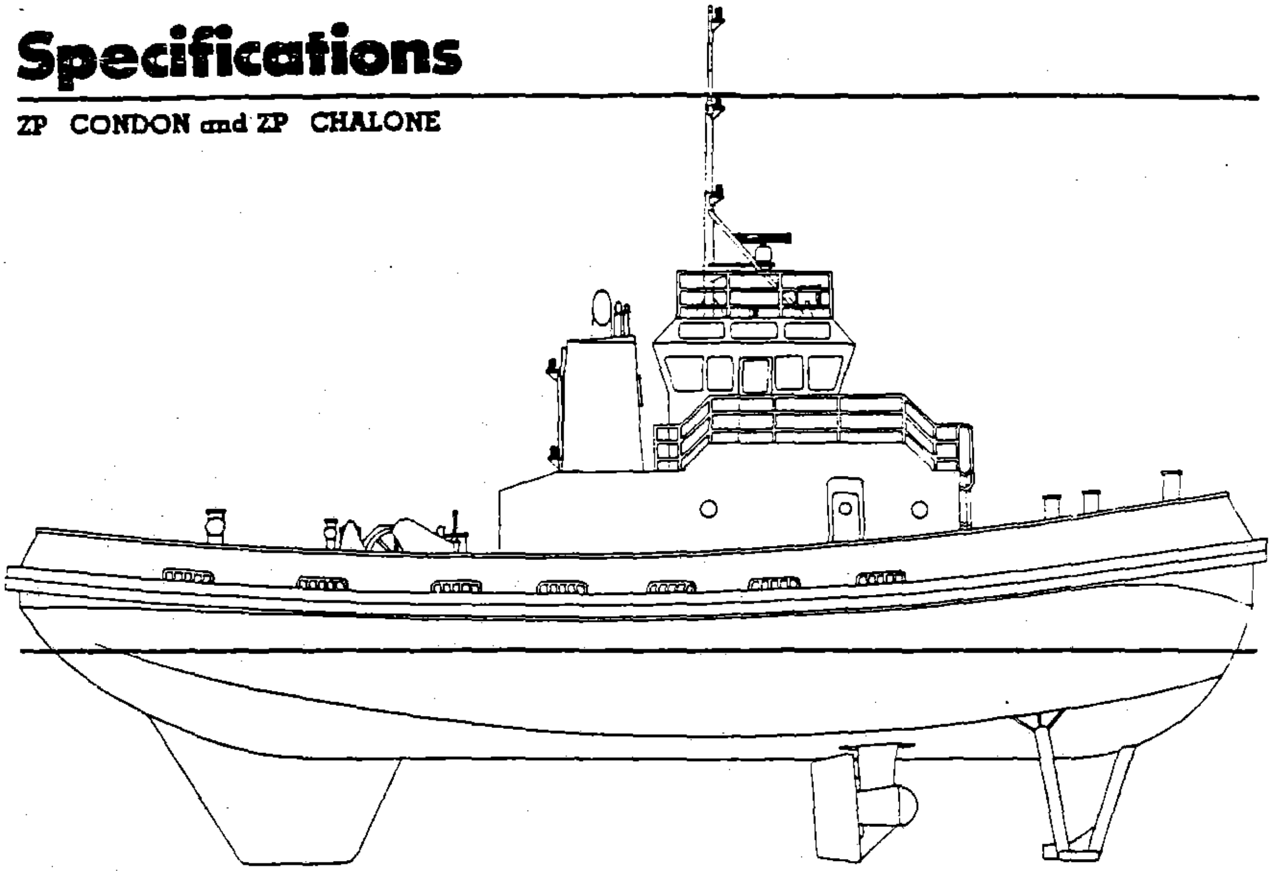


MODERN TRACTUG

FAUSTUG

Specifications

ZP CONDON and ZP CHALONE



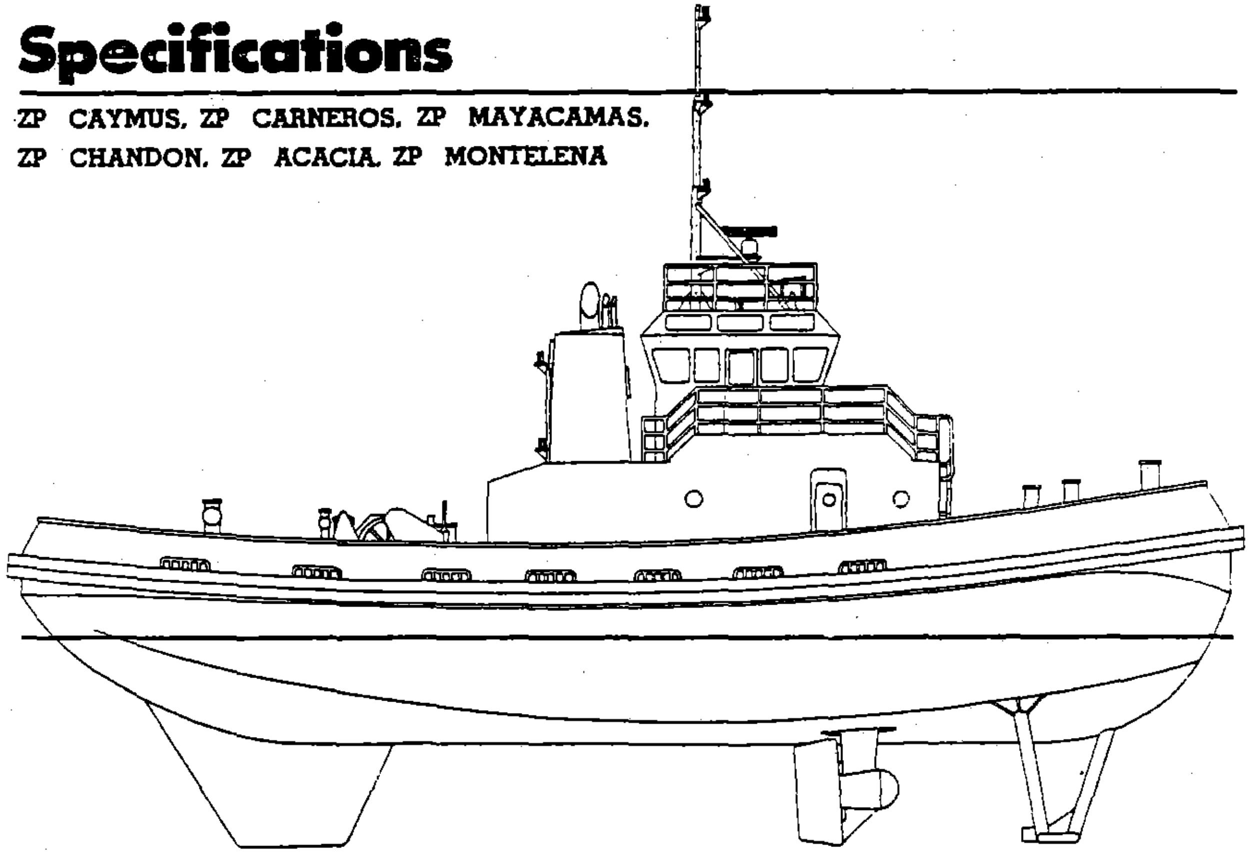
LENGTH – 93' 28.4 M **BEAM** – 34' 10.4 M **DRAFT** – 16' 4.9 M

TONNAGE	–	194 gross tons
RATED	–	ABS ✠ A-1 Ocean towing, ✠ AMS, ACCU USCG Load Line
ENGINES	–	Twin EMD 645 EMD 645 E6 Diesels 4000 HP 45 Tons ABS rated bollard pull.
PROPULSION	–	Niigata Z-peller 3-A units with 360° thrust & geared 1:2.792 Kaplan 4 bladed fixed pitch propellers mounted in 6'10" Kort nozzles
GENERATORS	–	Delco 6-71 99 KW
AUTOMATION	–	Megasystems ABS, ACCU
WINCHES	–	Intercon 700 meter, direct drive self spooling with extra improved P.S. wire, 120,000 lb. breaking strength
ELECTRONICS	–	Satellite Navigation JRC; Harris SSB 125 Watt Necode 325; Sperry Gypocompass SR130; Loran C Texas Instruments 9900; Raytheon Radar 6410; Gyro Auto Pilot Decca 450; Fathometers Raytheon D999; VHF-FM (2) Raytheon 55
FIRE & SAFETY	–	Aurora Fire Pumps, 1000 gallons per minute Halon Fire Extinguishing Equipment
POLLUTION	–	Red Fox Water Quality Control
FUEL CAPACITY	–	56,000 gallons 2800 mile range
BERTHS	–	5 Crew maximum
BUILT BY	–	VALLEY SHIPBUILDING, INC. BROWNSVILLE, TEXAS
Drilling rigs handled by this class vessel	–	Blue Water #4; Diamond M. Gem; El Dorado; Griffin Alexander; High Island #5; Keyes 250; Mister Mel; Penrod #50; Penrod #53; Penrod #66; Penrod #83; Rowan Parris; Sabine III; Vicksburg

FAUSTUG

Specifications

ZP CAYMUS, ZP CARNEROS, ZP MAYACAMAS,
ZP CHANDON, ZP ACACIA, ZP MONTELENA



LENGTH – 93' 28.4 M **BEAM** – 34' 10.4 M **DRAFT** – 16' 4.9 M

TONNAGE	– 194 gross tons
RATED	– ABS ✠ A-1 Ocean towing ✠ AMS, ACCU USCG Load Line
ENGINES	– Twin B&W Holeby Diesels 7S28LU 4200 HP 48 Tons bollard pull.
PROPULSION	– Niigata Z-peller 3-A units with 360° thrust & geared 1:2.792 Kaplan 4 bladed fixed pitch propellers mounted in 6'10" Kort nozzles
GENERATORS	– Caterpillar 6-360 135 KW
AUTOMATION	– Pan American Systems ABS, ACCU
WINCHES	– Intercon 650 meter, 120,000 lb line pull direct drive self spooling with extra improved 2" P.S. wire. Double drums on last four vessels
ELECTRONICS	– Satellite Navigation JRC Harris SSB 125 Watt Necode 325 Sperry Gypocompass SR130 Loran C Texas Instruments 9900 Raytheon Radar 6410 Gyro Auto Pilot Decca 450 Fathometers Raytheon D999 VHF-FM (2) Raytheon 55
FIRE & SAFETY	– Aurora Fire Pumps, 1000 gallons per minute Halon Fire Extinguishing Equipment
POLLUTION	– Red Fox Water Quality Control
FUEL CAPACITY	– 56,000 to 78,000 gallons fuel 2800 to 3900 mile range
BERTHS	– 5 Crew maximum
BUILT BY	– VALLEY SHIPBUILDING, INC. BROWNSVILLE, TEXAS

FAUSTUG

APPENDIX 4.

TECHNICAL DESCRIPTION OF AVAILABLE THRUSTERS

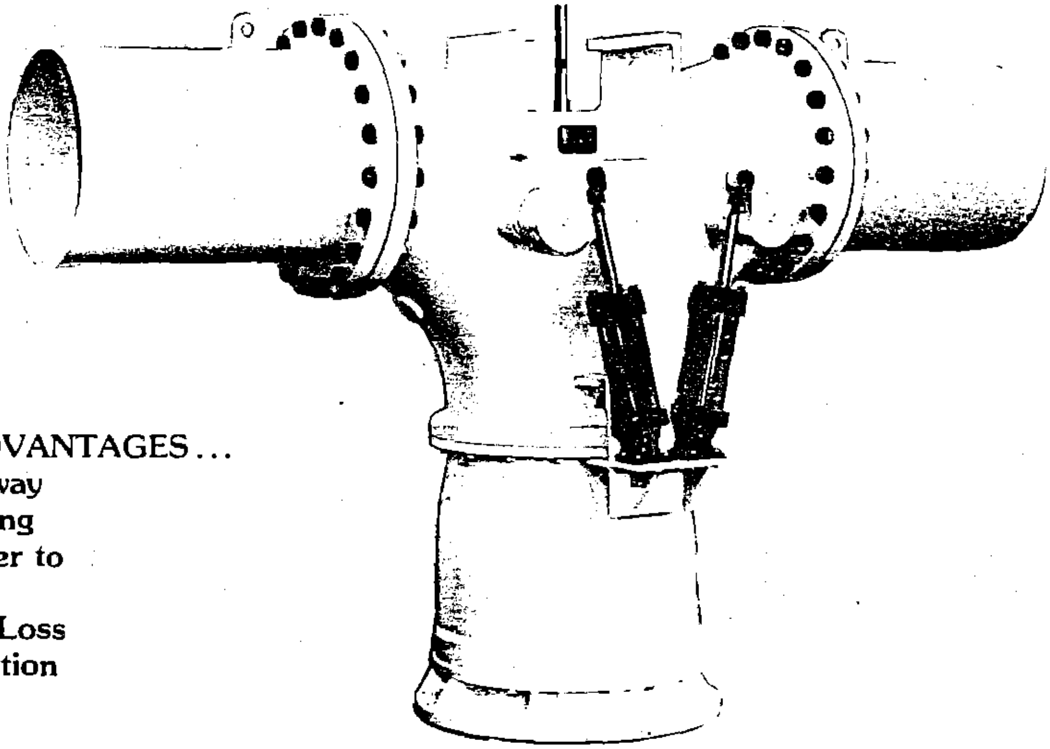
APPENDIX

Technical Descriptions of Available Thrusters

OMNITHRUSTER™

Maneuvering and Positioning Systems

PV SERIES . . . LOWEST-COST OMNITHRUSTER



PV SYSTEMS KEY ADVANTAGES . . .

- **More Thrust Underway**
- **Thrusts While Pitching**
- **No Reversing Impeller to Change Direction**
- **Minimum Buoyancy Loss**
- **Smaller Hull Penetration**
- **Fuel Savings**

The OMNITHRUSTER PV Systems direct thrust continuously through neutral, port or starboard without changing direction or speed of the prime mover. This results in a rapid response in positioning the bow, stern or the vessel itself. Thrust is produced continuously with nozzles in or out of the water, in rough seas, in strong currents, with vessel underway, or while pitching, rolling, yawing or heaving.

UNIQUE FEATURES INCLUDE . . .

- No rotating parts to be stopped or started. Produces thrust port and starboard without reversing motor.
- Mechanically simple; long service life.
- Easily maintained; can be serviced in the water.
- Control system with proprietary single level OMNITHRUSTER pneumatic logic valve and standard actuator cylinders and piping techniques for simplicity and reliability.
- Small jet openings — less than 20% of area of the hull penetration of conventional thrusters resulting in fuel savings, higher hull speed, reduced passage time.
- No protrusions — no change in hull shape.
- Designed to use standard shipyard construction techniques for speedier installation, minimizing labor . . . saving time and dollars.

LOW INVESTMENT . . . LOW INSTALLATION COSTS! THE PV SYSTEMS UTILIZE THE BASIC OMNITHRUSTER DESIGNS MAKING IT POSSIBLE TO RETROFIT OTHER OMNITHRUSTER FEATURES.

MODELS	H.P.	SHAFT RPM	IMPELLER THRUST LBS.	KGS	NOZZLE THRUST LBS.	KGS	MAX. NOZZLE DIA. INCHES	MM	APPROX. WEIGHT LBS.	KGS	OVERALL HEIGHT INCHES	MM	APPROX. BEAM WIDTH INCHES	MM	KEEL LINE LENGTH INCHES	MM
PV300	50	1,750	1,200	545	1,000	455	8.50	216	1.400	636	58	1,473	55	1,397	37	940
PV350	75	1,700	1,425	648	1,275	580	8.75	222	1.400	636	58	1,473	55	1,397	41	1,041
PV500	150	1,200	3,200	1,455	2,500	1,136	10.50	267	2.200	1.000	72	1,829	78	1.981	47	1,194
PV600	200	900	4,000	1,818	3,500	1,591	13.00	330	4.440	2.018	83	2.108	102	2,591	47	1,194
PV700	350	900	7,000	3,182	6,000	2,727	15.00	381	5.500	2.500	90	2,286	103	2,616	48	1,219
PV800	600	600	11,500	5,227	10,500	4,773	20.00	508	10.500	4,773	137	3,480	134	3.404	60	1,524
PV950	750	640	15,000	6,818	13,000	5,910	22.00	559	12.000	5,455	137	3,480	134	3,404	60	1,524
PV1100	1000	600	20,000	9,091	17,000	7,727	28.00	711	18,000	8,182	160	4,064	117	2,972	80	2,032

All details and specifications are subject to change; nozzle thrust is typical system thrust and varies by installation.

***OMNITHRUSTER INC.** manufactures a full range of Bow and Stern Systems, horizontal and vertical, powered by AC or DC electric, hydraulic or diesel drive, providing 25 to 1000 HP thrust modules which may be combined for any given horsepower requirements with impeller specific thrust ranging up to 24 lbs. per horsepower, subject to system effects due to installations and controls; operated by OMNITHRUSTER-Built Electronic Systems.

OMNITHRUSTER INC. 9515 Sorensen Ave., Santa Fe Springs, CA 90670 • (213) 802-1818 • Telex 194265 OMNI SFES

Cable Address: Omnithrust Printed in U.S.A. 1072/8/2

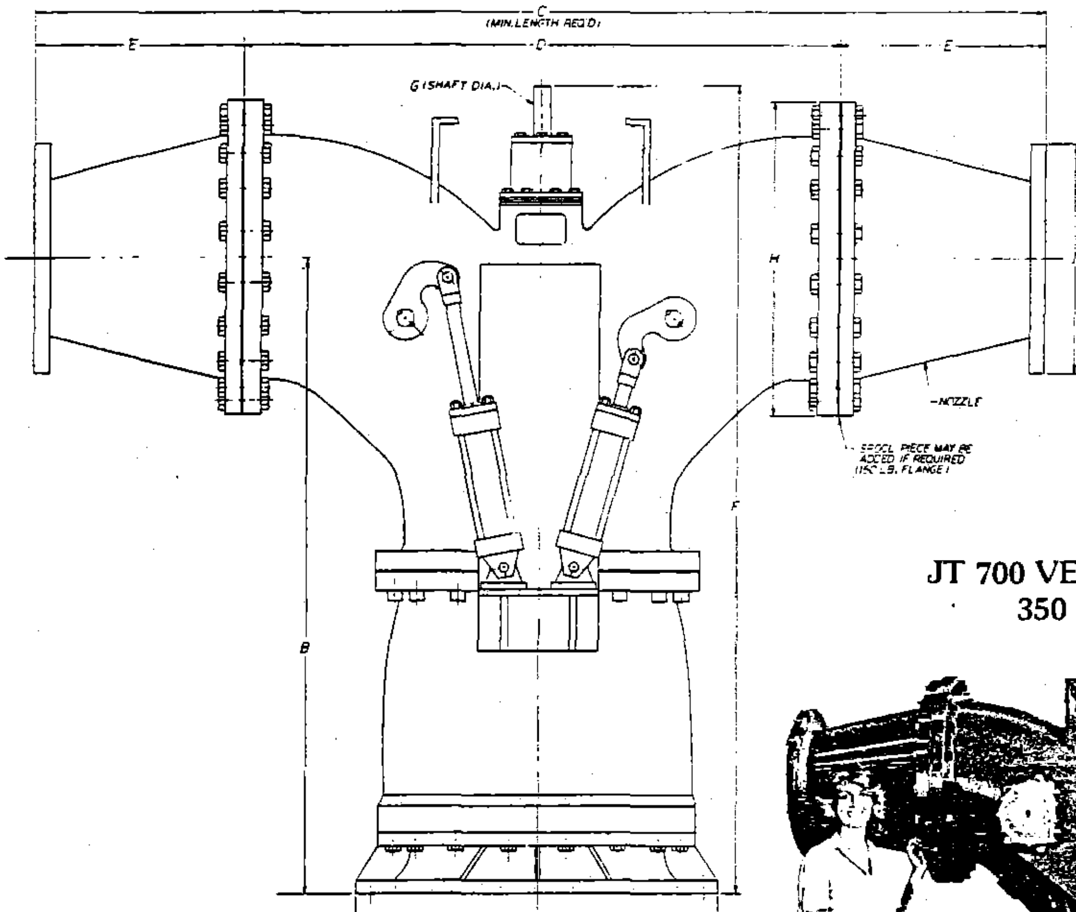
OMNITHRUSTER is more than a bow thruster. It does what a conventional bow thruster does, but its many unique features make it a complete maneuvering *system* in the harbor and at sea. Listed below are 11 basic OMNITHRUSTER systems which can be used in the bow or the stern and in various system combinations for increased thrust and control.

MODEL NUMBER	H P	SHAFT RPM	MAX.* RATED THRUST LBS	KGS	MAX NOZ DIA IN	MM	APPX WT LBS	KGS	A IN	MM	B IN	MM	C IN	MM	D IN	MM	E IN	MM	F IN	MM	G IN	MM	H IN	MM	I IN	MM	J** IN	MM
JT100	25	1,300	550	250	8.75	222	1,500	682	22	559	39	991	55	1397	34	864	10	254	52	1321	1.250	32	21	533	16	406	37	940
JT200	40	1,620	880	400	8.75	222	1,750	795	22	559	39	991	55	1397	34	864	10	254	52	1321	1.250	32	21	533	16	406	37	940
JT300	50	1,750	1,100	500	8.50	216	1,800	818	22	559	39	991	55	1397	34	864	10	254	52	1321	1.250	32	21	533	16	406	37	940
JT350	75	1,800	1,650	750	8.75	222	1,800	818	22	559	39	991	55	1397	34	864	10	254	52	1321	1.250	32	21	533	16	406	37	940
JT400	100	975	2,200	1000	10.50	267	4,600	2091	27	686	51	1295	70	1778	42	1067	18	457	65	1651	1.625	41	25	635	19	483	41	1041
JT500	150	1,200	3,300	1500	10.50	267	4,900	2227	27	686	51	1295	70	1778	42	1067	18	457	65	1651	1.625	41	25	635	19	483	41	1041
JT600	200	900	4,400	2000	13.00	330	6,800	3091	36	914	67	1702	103	2616	61	1549	21	533	85	2159	1.843	47	32	813	25	635	48	1219
JT700	350	900	7,700	3500	15.00	381	6,800	3091	36	914	67	1702	103	2616	61	1549	21	533	85	2159	1.843	47	32	813	25	635	48	1219
JT800	600	600	12,000	5455	20.00	508	11,500	5227	54	1372	96	2438	104	2642	76	1930	14	356	126	3200	4.000	102	41	1041	29	737	84	2134
JT950	750	640	15.000	6818	22.00	559	12.000	5455	54	1372	96	2438	104	2642	76	1930	14	356	126	3200	4.000	102	41	1041	29	737	84	2134
JT1100	1000	600	20,000	9091	28.00	711	18,000	8182	63	1600	125	3175	117	2972	–	–	18	457	151	3835	5.000	127	53	1346	–	–	103	2616

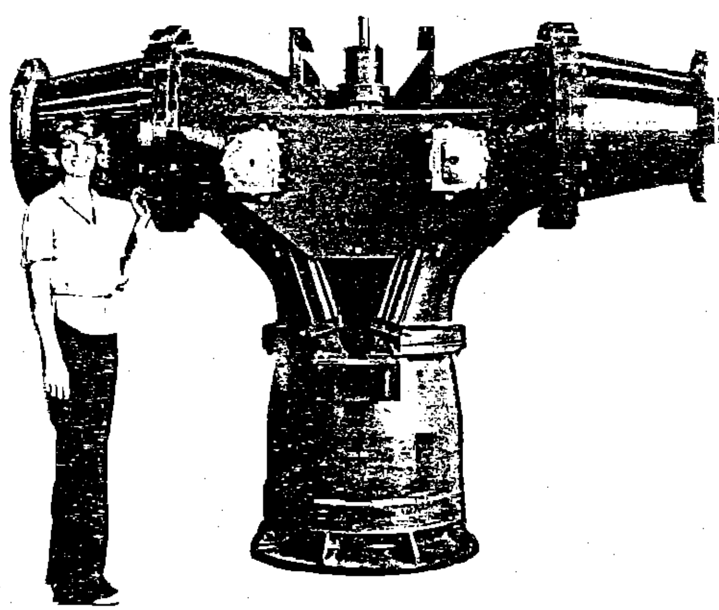
All details and static specifications are subject to change.

NOTE: * Maximum rated thrust does not include grid, suction and pipe losses. It may vary above or below the values depending on intake construction and other factors.

** Maximum length along keel is "J".



JT 700 VERTICAL SYSTEM
350 Horsepower



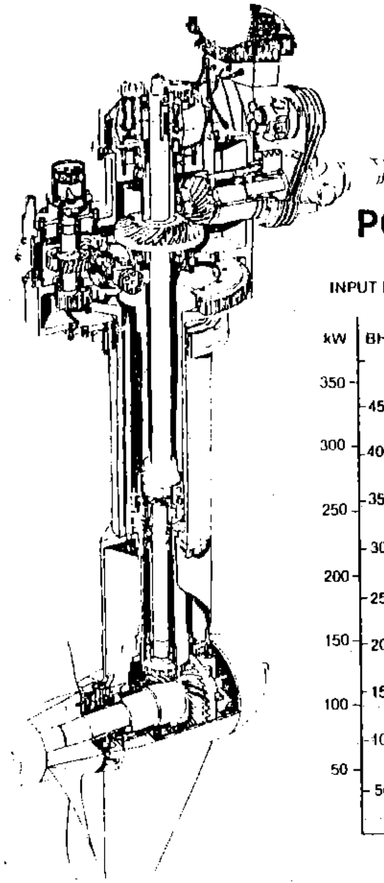
OMNITHRUSTER INC.

9515 Sorensen Avenue, Santa Fe Springs, California 90670
Telephone 213/802-1818
Telex 194265 OMNI SFES
Cable Omnithrust

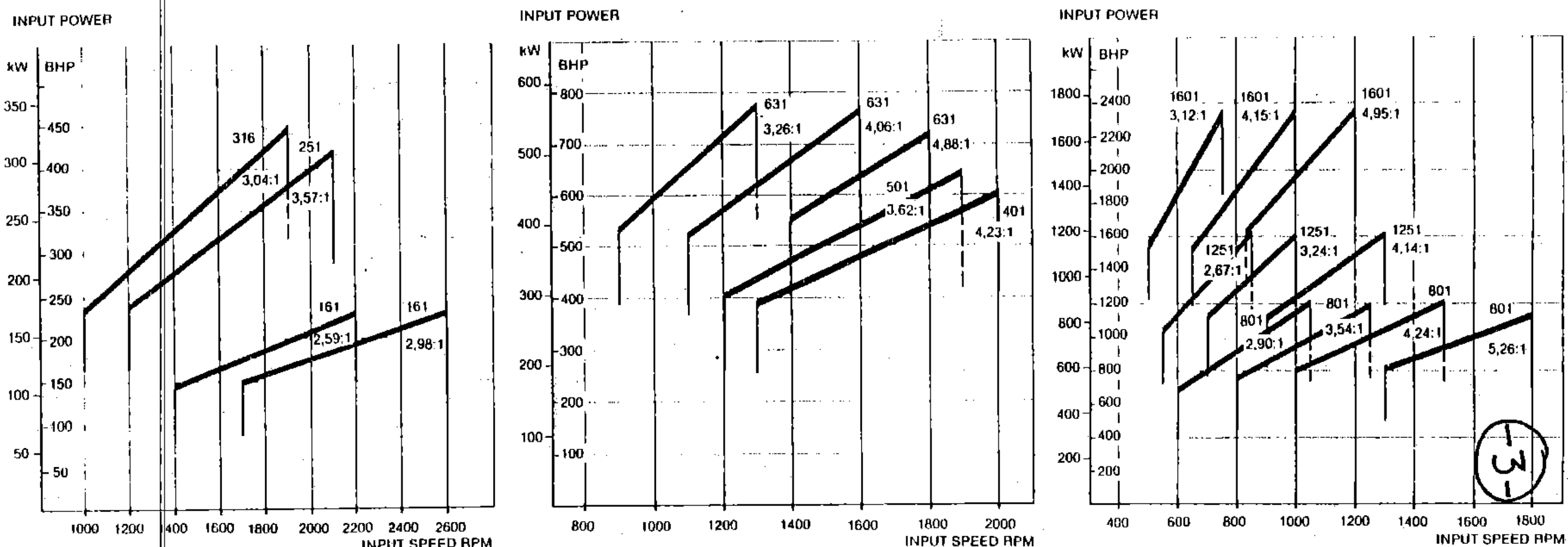
OMNITHRUSTER Systems Covered by U.S. Patents;
Foreign Patents Pending

(For HORIZONTAL CONFIGURATION: See Bulletin 1024/8-9)

AQUAMASTER



POWER RANGE



TECHNICAL DATA

Aquamaster size	161	251	316	401	501	631	801	1251	1601
Input power range (BHP)	120—235	200—420	220—450	300—600	330—650	450—800	700—1200	1000—1600	1500—2400
Input speed range (RPM)	1400—2600	1200—2100	1000—1900	1300—2000	1200—1900	900—1800	600—1800	600—1300	500—1200
Reduction ratios	2,59:1 2,98:1	3,57:1	3,04:1	4,23:1	3,62:1	3,26:1 4,06:1 4,88:1	2,90:1 3,54:1 4,24:1 5,26:1	2,67:1 3,24:1 4,14:1	3,12:1 4,15:1 4,95:1
Max screw diameter (mm)	900	1250	1250	1350	1350	1700	2000	2400	2800
Dry weight (kg, stem length 3000 mm)	1600	2400	2400	3500	3500	5600	7500	12500	18000
Stem lengths (mm) min. max.	1050 3500	1260 5000	1250 5000	1500 5750	1500 5750	1750 6000	2000 6000	2750 7000	2900 8000

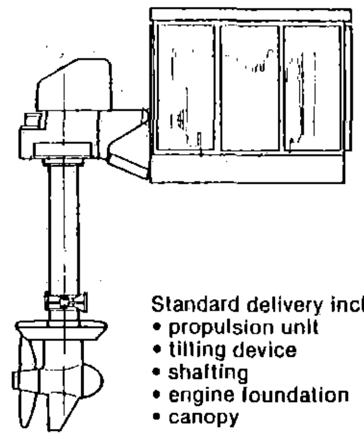
Specifications are subject to change without notice.

Where the units are subjected to light service only without classification, the outputs given above may be exceeded. Should this be done, it has to be separately agreed upon with the manufacturer.

(3)

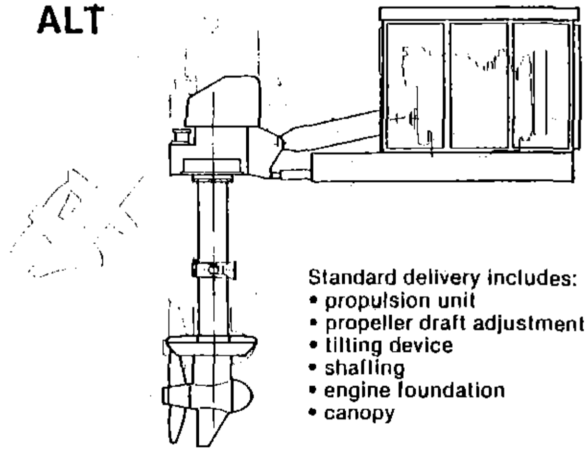
Basic types

AT



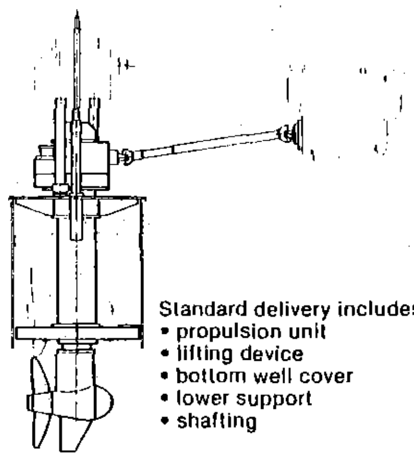
Standard delivery includes:
- propulsion unit
- tilting device
- shafting
- engine foundation
- canopy

ALT



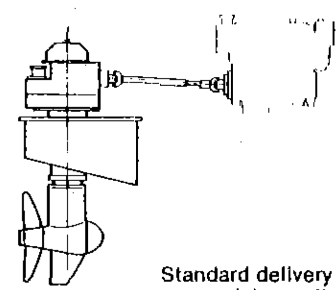
Standard delivery includes:
- propulsion unit
- propeller draft adjustment
- tilting device
- shafting
- engine foundation
- canopy

UL



Standard delivery includes
- propulsion unit
- lifting device
- bottom well cover
- lower support
- shafting

US



Standard delivery includes:
- propulsion unit
- bottom well cover
- shafting

Please indicate in your enquiry:
- AQUAMASTER type AT, ALT, US or UL
- AQUAMASTER size/stem length (mm)
- type of prime mover with power and input revs.
- type and speed of vessel
- classification, if any

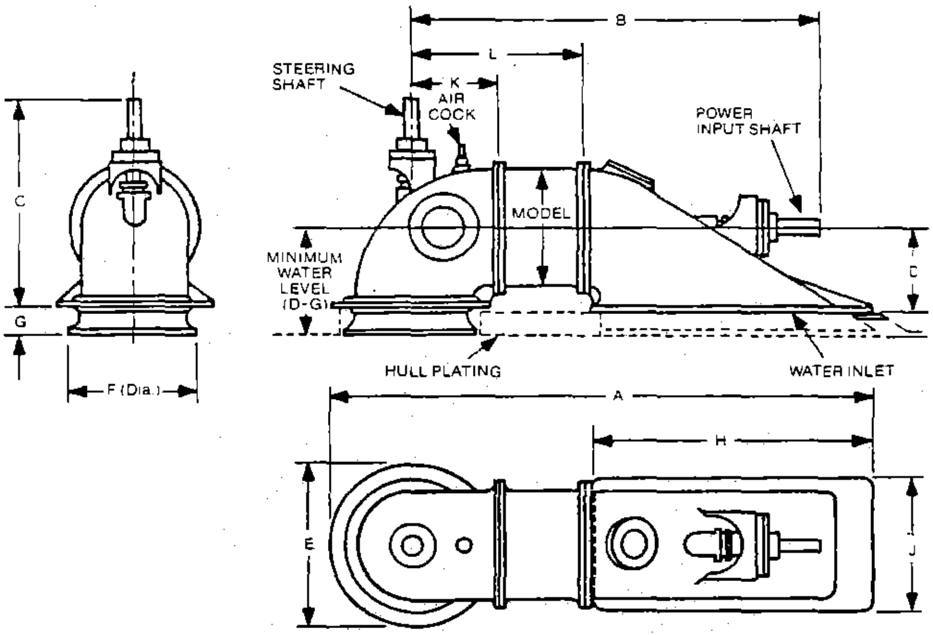
AQUAMASTER

HOLLMING LTD RAUMA FINLAND

26100 Rauma 10 Finland 958-38-15200 Telex 65-114

HA 32T 84 Prin

ELLIOTT WHITE GILL



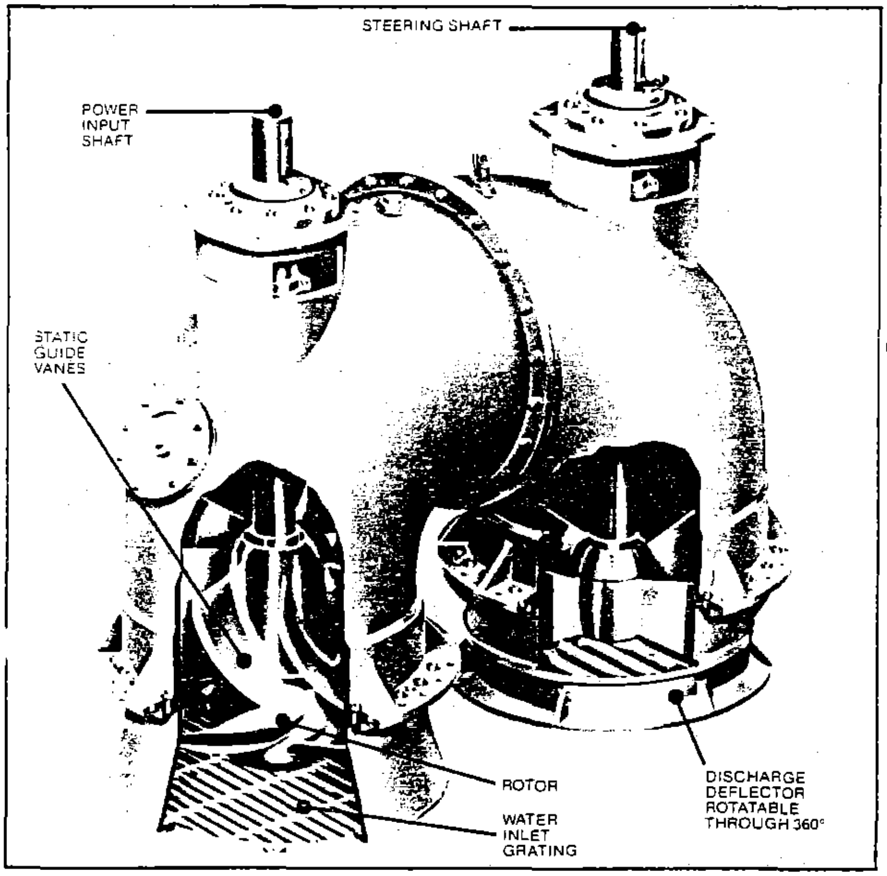
Series	Model	r/min	hp (absorbed)	Static thrust lb/kg	A	B	C	D	E	F	G	H	J	K	L	Approx. weight lb/kg	Rotation
					Dimensions (Upper Inches/*Lower Millimeters*)												
Series I	12-I	2000	56	770 *349*	65 *1651*	51⅛ 1299	23⅛ *587*	9 *229*	19¾ *502*	14 *356*	2¾ *70*	33¾ *857*	16⅛ *410*	10¾ *273*	20⅜ *518*	569 *258*	Both
	14-I	1714	76	1060 *481*	73½ *1867*	58⅝ *1489*	27¾ *705*	10½ *267*	21¾ *552*	17½ *445*	3½ *89*	39 *991*	18½ *470*	11½ *292*	22½ *572*	832 *378*	Both
	16-I	1500	100	1400 *635*	83⅞ *2130*	64¼ *1632*	30¾ *781*	12 *305*	24½ *622*	20 *508*	4 *102*	44⅝ *1133*	21⅜ *543*	13 *330*	25¾ *654*	1266 *574*	Both
	20-I	1200	155	2210 *1003*	105¾ *2686*	84⅝ *2149*	36⅝ *930*	15 *381*	32½ *826*	25 *635*	5 *127*	54¼ *1378*	26 *660*	17¾ *451*	33¾ *857*	2380 *1080*	Both
	24-I	1000	222	3220 *1461*	122¼ *3105*	97½ *2477*	43½ *1105*	18 *457*	36 *914*	27⅞ *708*	5½ *140*	63½ *1613*	30½ *775*	19¾ *502*	38 *965*	3680 *1670*	Both
	32-I	750	389	5910 *2681*	143 *3632*	116⅞ *2968*	56⅝ *1438*	24 *609*	49 *1245*	40 *1016*	8⅜ *213*	63 *1600*	49 *1245*	26 *660*	51 *1295*	7840 *3550*	Clockwise
	40-I	600	601	9500 *4310*	176 *4474*	141½ *3594*	66⅜ *1686*	30½ *775*	60 *1524*	50 *1270*	22 *559*	81 *2058*	60 *1524*	32 *813*	52 *1320*	16240 *7400*	Counter-clockwise
	50-I	480	925	15370 *6974*	225 *5715*	175⅝ *4462*	80½ *2046*	38 *965*	74 *1880*	62½ *1588*	13½ *342*	105 *2665*	74 *1880*	40 *1016*	76 *1931*	29800 *13500*	Counter-clockwise

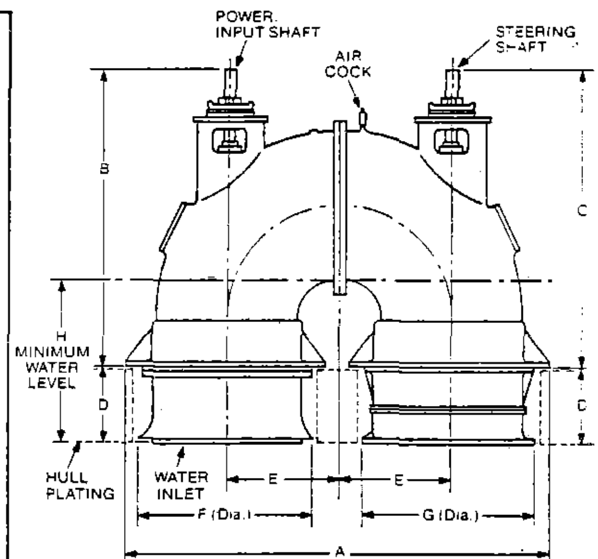
Series	Model	r/min	hp (absorbed)	Static thrust lb/kg	A	B	C	D	E	F	G	H	J	K	L	Approx. weight lb/kg	Rotation
Series II	12-II	2000	110	1120 *503*	74⅝ *1895*	62⅜ *1584*	23⅛ *587*	9 *229*	19¾ *502*	15 *381*	3 *76*	33¾ *857*	16⅛ *410*	10¾ *273*	30 *762*	659 *299*	Both
	14-II	1714	150	1550 *703*	84½ *2146*	69⅝ *1768*	27¾ *705*	10½ *267*	21¾ *552*	17½ *445*	3½ *89*	39 *991*	18½ *470*	11½ *292*	33½ *851*	970 *440*	Both
	16-II	1500	195	2060 *935*	96⅝ *2454*	79½ *2019*	30¾ *781*	12 *305*	24½ *622*	20 *508*	4 *102*	44⅝ *1133*	21⅜ *543*	13 *330*	38½ *978*	1480 *672*	Both
	20-II	1200	304	3280 *1488*	121¾ *3092*	101 *2565*	36⅝ *930*	15 *381*	32½ *826*	25 *635*	5 *127*	54¼ *1378*	26 *660*	17¾ *451*	49¾ *1264*	2880 *1310*	Both
	24-II	1000	435	4770 *2164*	140½ *3569*	115¾ *2940*	43½ *1105*	18 *457*	36 *914*	27⅞ *708*	5½ *140*	63½ *1613*	30½ *775*	19¾ *502*	56¼ *1429*	4560 *2070*	Both

Refer to notes on page 6.

-6-

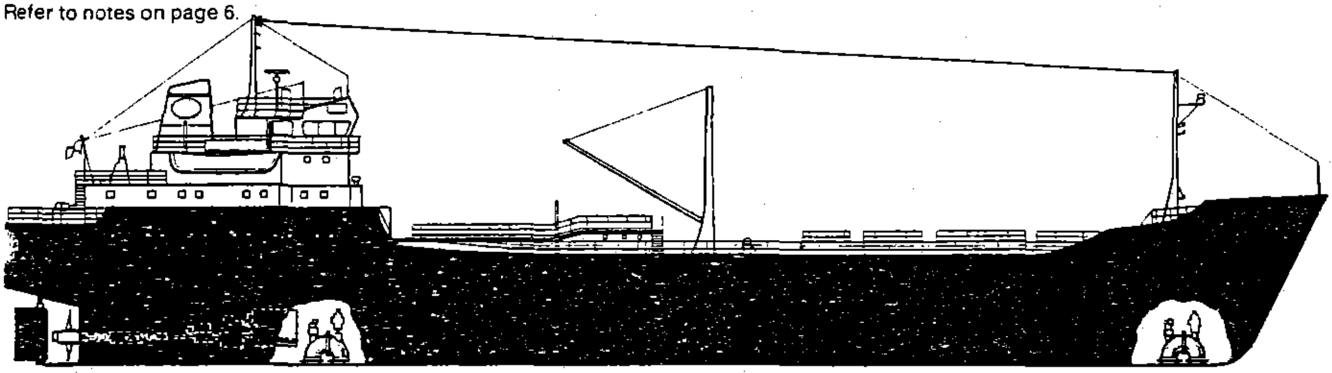
Elliott Vertical Shaft White Gill™ Unit



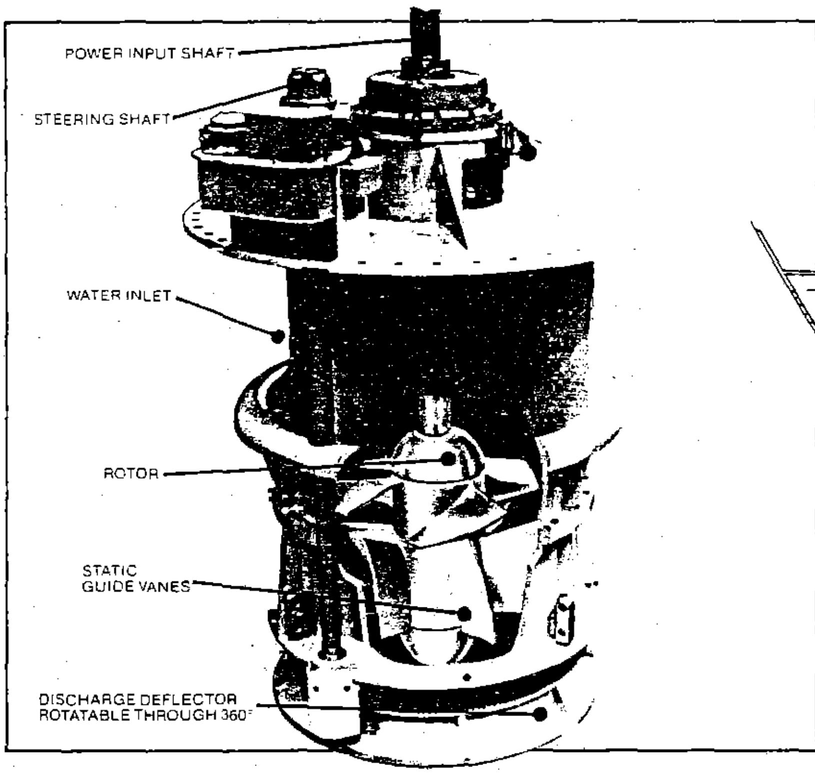


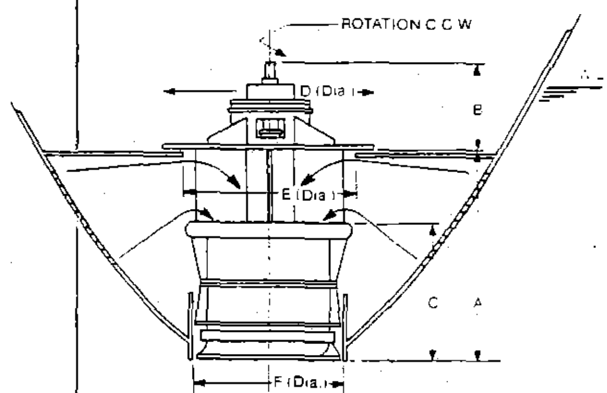
Model	r/min	hp (absorbed)	Static thrust lb/kg	Dimensions (Upper Inches/*Lower Millimeters*) A	B	C	D	E	F	G	H	Approx. weight lb/*kg*	Rotation
24	1000	222	3220 *1461*	75¾ *1924*	60 *1524*	57 *1448*	14 *356*	21 *533*	31 *787*	30 *762*	26 *660*	4480 *2030*	Clockwise
32	750	389	5910 *2681*	101 *2565*	72½ *1842*	69¼ *1759*	17 *432*	26 *660*	40½ *1029*	40 *1016*	34 *864*	8960 *4060*	Counter-clockwise
40	600	601	9500 *4310*	124 *3150*	85¼ *2165*	81¾ *2076*	22 *559*	32 *813*	51 *1295*	50 *1270*	45 *1143*	15680 *7110*	Clockwise
50	480	925	15370 *6974*	154 *3912*	104 *2642*	100½ *2553*	27½ *700*	40 *1016*	63 *1600*	62½ *1588*	60 *1524*	31360 *14230*	Clockwise

Refer to notes on page 6.



Elliott T3 White Gill™ Unit



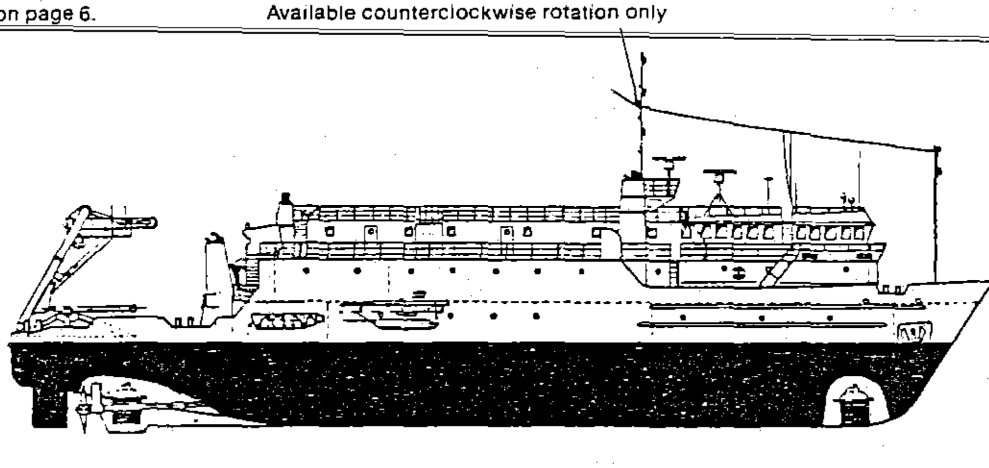


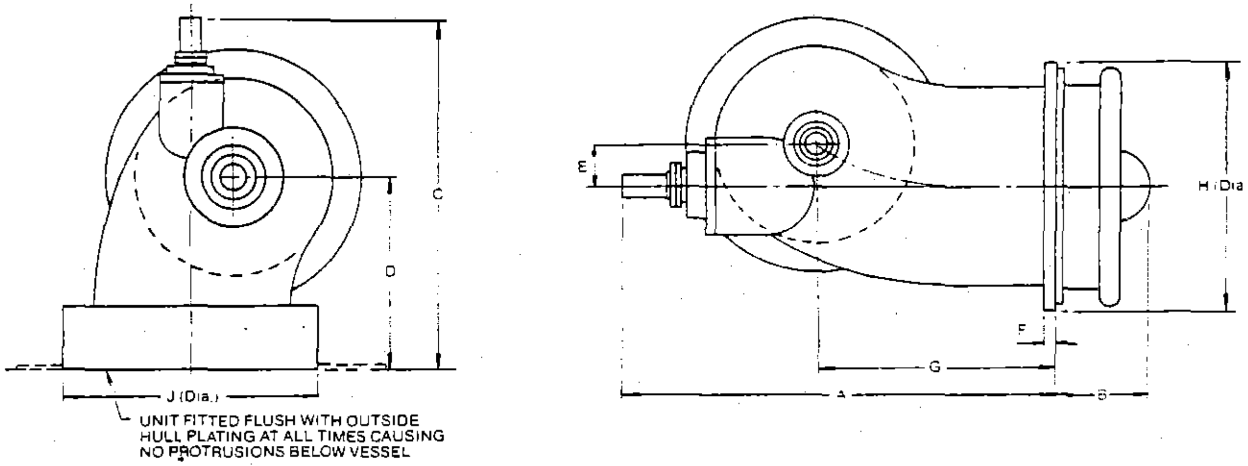
Model	r/min	hp (absorbed)	Static thrust lb/kg	Dimensions (Upper Inches/*Lower Millimeters*) A	B	C	D	E	F	Free intake area ft²/*m²*	Approx. weight lb/*kg*
32	781	469	7270 *3300*	61[illegible] *1556*	28⅜ *720*	33⅞ *981*	56[illegible] *1430*	46⅞ *1190*	41 *1043*	14 *1.30*	8310 *3770*
40	625	725	11680 *5300*	75 *1905*	33½ *850*	48 *1220*	68[illegible] *1735*	58 *1475*	51[illegible] *1305*	22 *2.03*	11245 *5100*
50	500	1117	18730 *8500*	91[illegible] *2324*	36⅞ *935*	60 *1524*	83 *2110*	72 *1830*	64[illegible] *1630*	35 *3.20*	20280 *9200*
60	417	1608	27430 *12400*	115⅞ *2943*	50 *1270*	72[illegible] *1843*	98[illegible] *2510*	86⅝ *2200*	77 *1955*	49 *4.56*	32110 *14570*
70	357	2189	37730 *17100*	130[illegible] *3307*	39[illegible] *1005*	84 *2135*	115[illegible] *2935*	102 *2590*	89[illegible] *2280*	67 *6.21*	47700 *21640*

15.50
16.1
16.8
17
17 lbs/HP

Refer to notes on page 6.

Available counterclockwise rotation only

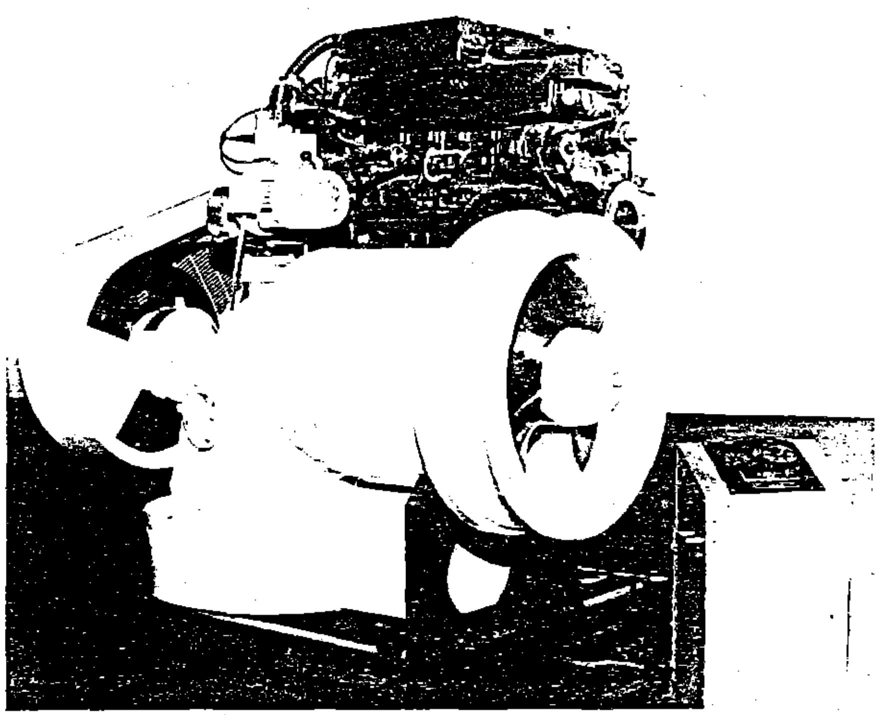




Model	r/min	hp (absorbed)	Static thrust lb/kg	Dimensions (Upper-Inches/*Lower Millimeters*) A	B	C	D	E	F	G	H	J	Free intake area ft²/*m²*	Approx. weight lb/*kg*
20	1200	155	2210 *1003*	53⅜ *1357*	8½ *215*	37⅜ *950*	23⅝ *600*	4⅝ *117*	1 *25*	35⅞ *910*	26¾ *680*	26⅝ *675*	4.5 *0.41*	1876 *851*
24	1000	222	3220 *1461*	65⅛ *1655*	11⅜ *288*	45⅝ *1160*	28⅜ *720*	5½ *140*	1⅛ *30*	42⅞ *1090*	32½ *825*	31⅞ *810*	6.3 *0.58*	2977 *1350*
32	750	389	5910 *2681*	81½ *2070*	15⅛ *383*	61⅜ *1560*	37¾ *960*	7½ *190*	1⅝ *40*	57¼ *1455*	42⅞ *1088*	42½ *1080*	11.3 *1.04*	5437 *2463*
40	600	601	9500 *4310*	104⅜ *2650*	19 *480*	75⅞ *1925*	47¼ *1200*	9½ *240*	2 *50*	71¾ *1820*	57 *1450*	53¼ *1350*	18.0 *1.62*	10600 *4800*

Refer to notes on page 6.

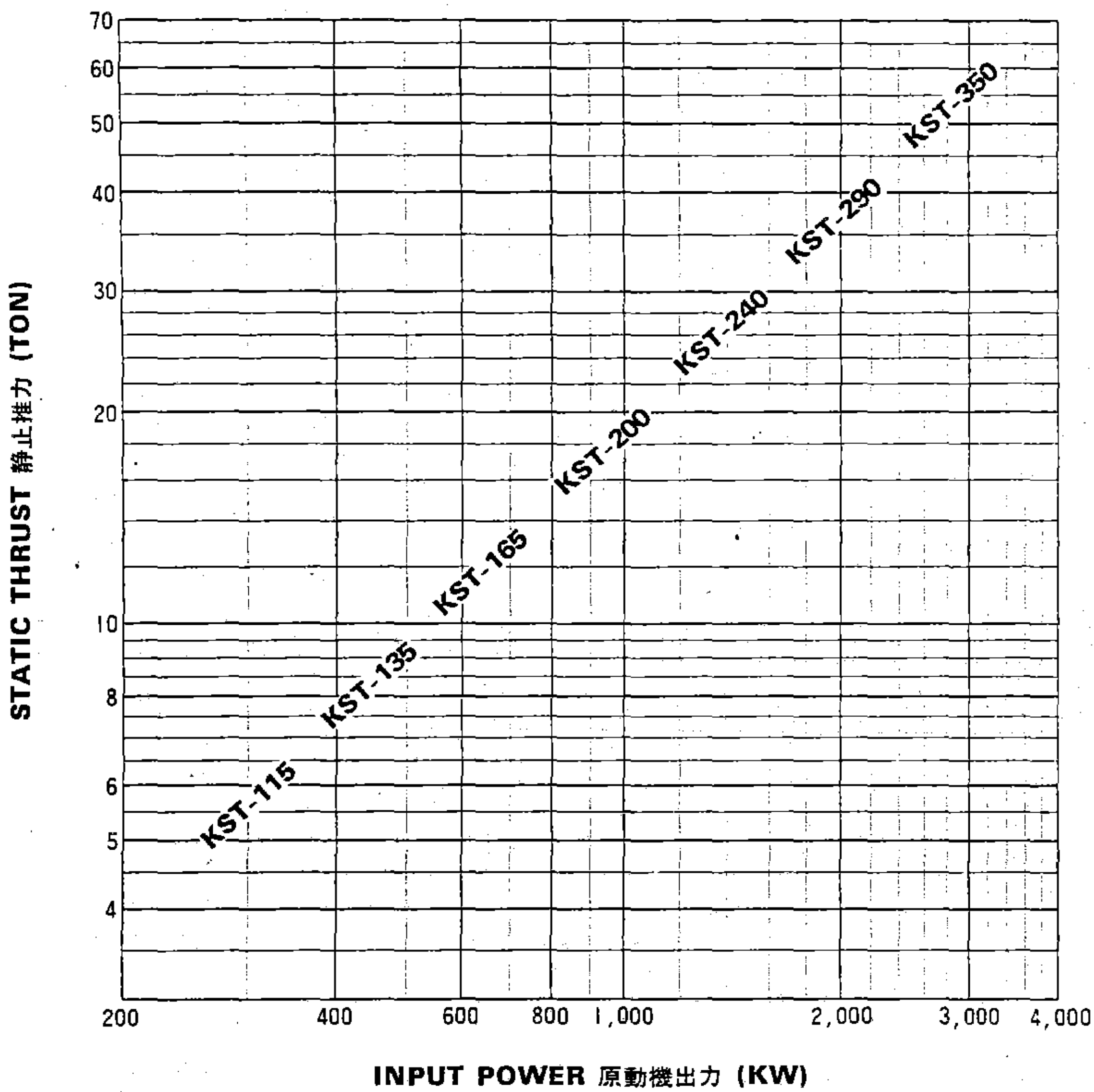
Available counterclockwise rotation only



The Cross Shaft White Gill unit is available with a belt driven piggy-back engine as pictured. This small, easy to install package concept is available with a choice of drivers. Controls can be integrated to include thruster and driver in one simple panel. Dimensions and ratings of thruster are as listed; package dimensions are dependent upon engine.

SELECTION
型式選定

-9-
KAWASAKI



Type 型式	Propeller diameter プロペラ径 (M)	Max. Input power 最大入力馬力 (kW)	Input shaft speed 入力軸回転数 (REV/MIN)	Steering speed 旋回速度 (S 180°)	Pitch controlling speed 変節速度 (S 50°)	Max. Static thrust 最大静止推力 (TON)
KST-115	1.15	390	1,160	12	12	6.7
KST-135	1.35	540	1,160	12	12	9.2
KST-165	1.65	800	880	12	12	13.9
KST-200	2.0	1,180	700	12	12	20.2
KST-240	2.4	1,700	700	15	15	29.0
KST-290	2.9	2,430	580	18	18	41.4
KST-350	3.5	3,600	440	20	20	61.8

DIMENSIONS
主要寸法

KAWASAKI

Thruster units/スラスタユニットの外形寸法

(mm)

Type 型式		A	B	C	D	E	F	G	H
KST-115	LF/ZF	1,290	450	550	1,150	1,411	895	870	1,765
	LC/ZC	1,560	515	620	1,150	1,324	895	870	1,915
KST-135	LF/ZF	1,510	525	645	1,350	1,656	1,050	1,020	2,065
	LC/ZC	1,795	580	705	1,350	1,554	1,050	1,020	2,245
KST-165	LF/ZF	1,840	640	785	1,650	2,024	1,280	1,245	2,525
	LC/ZC	2,200	710	865	1,650	1,899	1,280	1,245	2,740
KST-200	LF/ZF	2,225	775	950	2,000	2,453	1,550	1,505	3,055
	LC/ZC	2,660	860	1,045	2,000	2,302	1,550	1,505	3,315
KST-240	LF/ZF	2,670	930	1,140	2,400	2,944	1,860	1,810	3,670
	LC/ZC	3,200	1,035	1,255	2,400	2,762	1,860	1,810	3,985
KST-290	LF/ZF	3,230	1,125	1,380	2,900	3,557	2,250	2,185	4,435
	LC/ZC	3,860	1,250	1,515	2,900	3,338	2,250	2,185	4,810
KST-350	LF/ZF	3,900	1,360	1,665	3,500	4,293	2,715	2,635	5,350
	LC/ZC	4,660	1,505	1,830	3,500	4,029	2,715	2,635	5,805

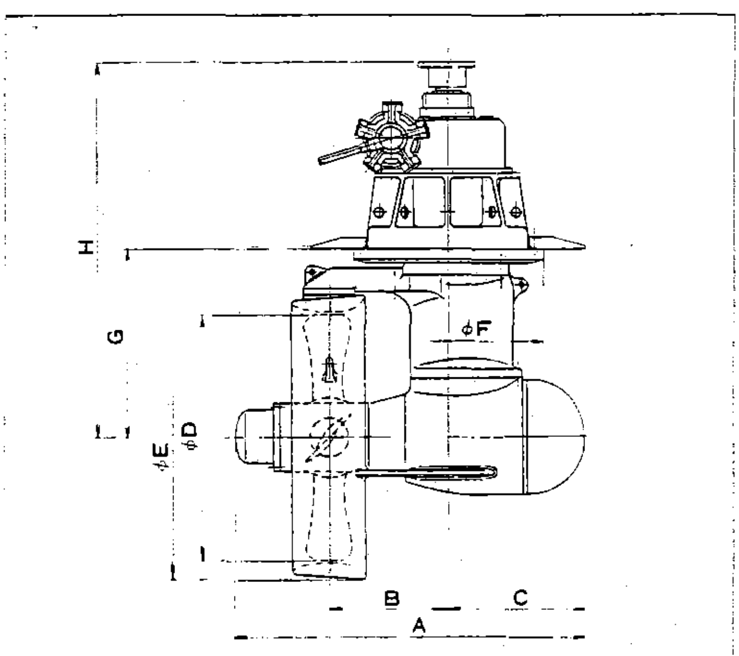
(Note) The standard dimensions shown in the above table are subject to some change in actual installations.
本表は標準寸法です。実機の場合、多少変更されることもありますので、ご了承ください。

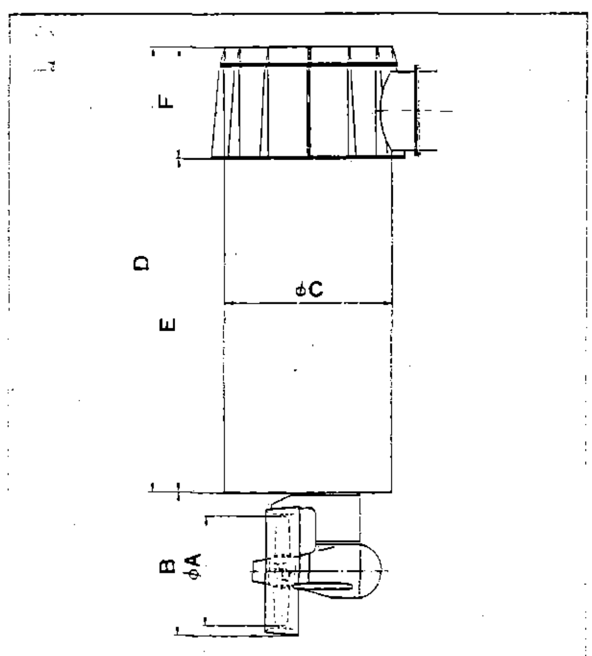
Container type thruster/コンテナ型の外形寸法

(mm)

Type 型式	A	B	C	D	E	F
KST-115	1,150	1,500	3,300	7,400	5,100	2,300
KST-135	1,350	1,800	3,300	7,400	5,100	2,300
KST-165	1,650	2,200	3,400	7,600	5,300	2,300
KST-200	2,000	2,600	3,600	8,000	5,600	2,400
KST-240	2,400	3,100	3,900	8,700	6,100	2,600
KST-290	2,900	3,800	4,400	9,800	7,000	2,800
KST-350	3,500	4,600	5,100	11,400	8,400	3,000

(Note) Kawasaki will accept your request for any change in these standard dimensions.
ご希望により、標準寸法以外のコンテナ型も製作します。





SCHOTTEL-LIPS

Selection data

Series		300	350	500	1000	1100	1500	2500	4500
Max. power input* (kW)		480	660	1000	1250	1750	2000	3000	4500
Max. input speed* (rpm)	Z drive	1800	2200	1800	1250	1300	1300	1200	1000
	L drive	1300	1800	1600	900	1000	1000	900	750
Propeller diameter (mm)	Max.	1550	1900	2300	2600	2700	2900	3300	5400
	Standard	1400	1700	2100	2300	2600	2600	3200	4200
Max. thrust in bollard pull (kN)**	D.P.	85	125	185	230	315	350	520	815
	Intermittent	80	115	170	210	290	325	485	755
	Continuous	70	100	140	180	250	285	420	655
Propeller arm length (PAL mm)	Max.	4750	5000	5600	5600	5600	7300	9500	10000
	Min.	1750	2200	2600	2900	2900	3300	4550	5400
Weight (kg) Z drive, incl. nozzle	At min. PAL	3000	6300	9000	14500	17000	22000	35000	65000
	Extra per 100 mm PAL	40	40	65	100	100	130	200	280

* *Note: maximum power and maximum input speed do not necessarily coincide.*
** *1 kN = 102 kg force.*

These data are intended for use in preliminary design studies and are not binding.
The series indications are based on standard lower gearboxes; by choosing different lower gearbox and, in Z drives, upper gearbox reduction ratios a large range of input speeds may be accommodated.
The 'maximum thrust' figures are based on the standard propeller diameter and suitable input speed and reflect the allowable loading of gears for different applications; the installed power should be reduced from the stated DP power input by 10% for intermittent and 25% for continuous full load service.

We shall be pleased to assist you with the selection of the optimal units for your application, for which we would like to receive the following information as far as available:

1) Type and purpose of vessel

2) Type and purpose of thrusters

3) General arrangement drawing of vessel

4) Design conditions, i.e.
- vessel speed
- motor rpm
- required thrusts under transit and/or DP conditions
- estimated yearly operating hours of thrusters in transit and/or DP mode

5) model tests

The heart of the system

The Rudderpropeller

SCHOTTEL-LIPS

The Principle

During the past thirty years, the SCHOTTEL Rudder-Propeller (SRP) has been further developed into an all-purpose propulsion system, which has been service-proven in all parts of the world under the most extreme conditions. Its efficiency and sturdiness are proven, and its versatility is nearly unlimited.

The units can be installed in various ways as required, depending on the type of vessel, its operational purpose, the environmental conditions and the mounting position on or below deck.

The 'SCHOTTEL Rudder-Propeller' is the nucleus of a 'SCHOTTEL PROPULSION UNIT'. Built utilizing the latest technology, it transforms the engine power into optimum thrust by use of specially designed gears and a proportional propeller. Full thrust is provided to manoeuver the ship in any direction by rotating the lower gearbox, a principle which is as simple as it is effective, without power loss, with maximum manoeuvering capability, with unrestricted operational capacity, at full power ahead and astern; in addition to being economic, easily serviced, and space-saving in its installation.

Operation and Design

Power is transmitted by the SCHOTTEL RUDDER-PROPELLER through spiral bevel or planetary gears made of high tensile material which are casehardened, lapped in pairs and run silent. The reduction rations range from i=2,5:1 to 5:1, depending on the size of the unit. Packing seals are fitted throughout. The shafts are made of high tensile steel, the casing at the motion points of the seals consists of corrosion proof material.

All Rudderpropellers have, depending on their operational range, either a fully flooded or forced lubrication system.

The 3 or 4-bladed propellers are designed to suit the individual vessel. Depending on the unit, these propellers are of push or pull type and can be delivered in right or left turning rotation. Rudderpropellers with controllable pitch blades are also part of the production programme.

The steering is effected either mechanically, hydraulically or electrically.

The correct size of the Rudder-Propeller unit is chosen in accordance with the torque developed by the engine and the operating conditions; such as type of craft, speed required, and field of operation. Rudder-Propellers are available in many sizes. The standard type units cover a power range from 20 to 4500 kW (28 - 6150 HP). Special designs are possible.

The designation for the different propeller types refers to the maximum continuous torque (Nm) at the power intake, depending on the engine speed and power.

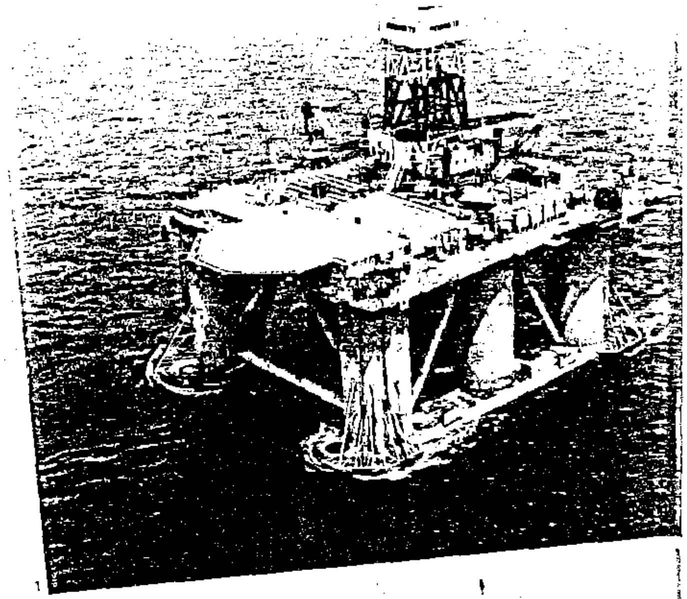
SCHOTTEL-Ruderpropeller (SRP) Standard Model Series

Type SRP		50 51	100 103	150 152	152 151	300 226	300 300	350 350	351 350	351 351	502 503	502 502	505 505	506 505	503 505	1000 1000	1100 1100	1500 1500	2500 2500	4500 4500
Max. Power kW		100	210	250	300	350	480	660			810	975	1000			1325	1750		2750	4500
	HP metric	135	285	340	400	475	650	900			1100	1325	1350			1800	2400		3750	6150
Nominal input torque Nm		420	850	1350	1675	2050	2800	3900	7000	5700	6200	8700	7300	8500	10600	16600	17200	21000	29000	67000
Max. r. p. m.		2500	2350	2000	2000	1800			1000	1300	1250	1050	1680	1400	1100	1000	1000			750
Reduction ratio		2,50	2,68	3,02	3,46	3,32	3,97	4,99	2,78	3,34	3,90	3,25	5,08	4,34	3,32	2,72 -3,77	4,12	3,20 -4,28	4,95	4,81
Propeller Diameter mm.	Max.	800	950	1100	1150	1350	1550	1900			2300		2100			2400	2700	2800	3500	4200
	Min.	600	700	900	900	1100	1250	1500			1900		1600			2100	1900	2500	3200	–
Propeller Arm-Length PAL mm	Max.	2800		4250		4750		5000			5600		5500			5600	5600	7300	9500	–
	Min.	875	980	1400		1750		2200			3000		2600			2900	3200	3100	4550	5400
Weight Without Nozzle With oil; kg	for min. Sternlength	190	300	880	1050	1600	2000	4000			5700		6500			9500	10000	16000	22000	32000
	per 100 mm add Sternlength	9	20,4	20,7	26	36,3	40	40			63,5		60			90	100	130	200	–

Nominal torque values are given for average conditions. The kind of operation, the type of prime mover or the sort of vessel may influence the actual allowable input torque figure. It is recommended to consult our technical staff before selecting the definite Rudderpropeller size.

The above technical data are not binding and may be changed at any time.

CONTAINERIZED THRUSTERS -13-



Containerized thrusters for use on semi-submersibles

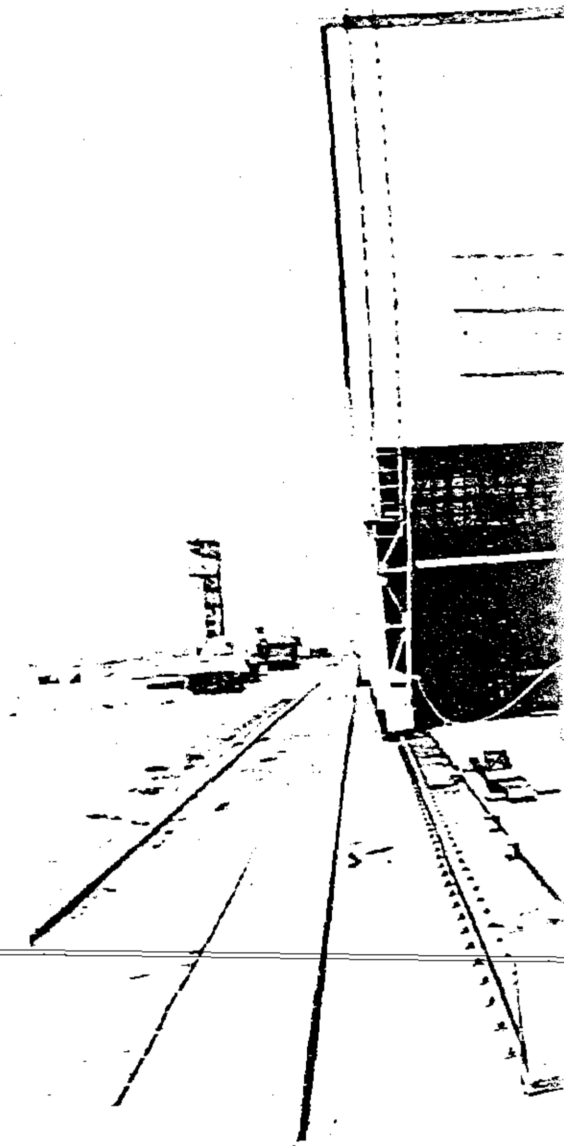
Powers up to 4500 kW   SCHOTTEL-LIPS

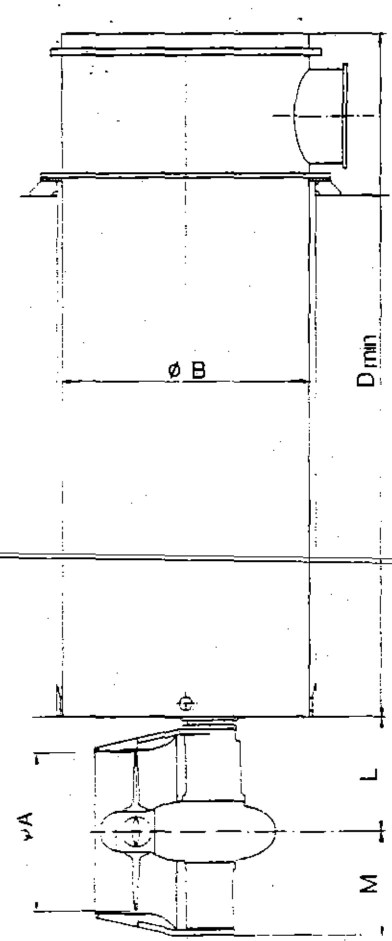
L drives

FP and CP propellers

Each thruster is installed in a cylindrical steel capsule which also houses the vertical main electric motor with auxiliaries.
The lower gearbox with propeller and nozzle projects from the bottom of the capsule; the bolted top is removable to facilitate installation and removal of all equipment.

At the vessel's pontoon height the capsule is equipped with a mounting flange and near its bottom it is fitted with three adjustable thrust blocks for connection to the vessel's thruster well.
The upper part is fitted with an access tube to one of the vessel's columns, through which the necessary piping and cabling are led.





Type	A	B	D_{min}	L	M
500	2100	3100	7000	1560	1290
1000	2300	3300	7500	1710	1410
1100	2400	3600	7500	1780	1470
1500	2600	3600	7500	1900	1600
2500	3200	4500	10000	2370	1960
4500	4200	6000	12000	3110	2560

The choice of propeller size

Main dimensions of the Voith-Schneider Propeller

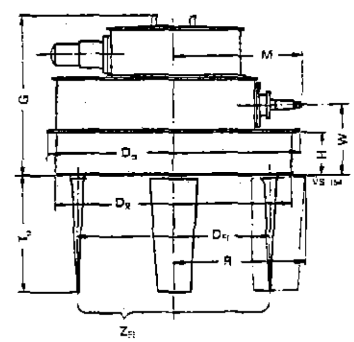
The size of the VSP is determined not -ly from hydrodynamic considerations, ; also on its suitability for the mechanical loads which propeller thrust and torque exert on the blades and driving parts. As each case is judged individually, we must reserve the right to choose the propeller to be used. However, for consideration at the initial project stage, the permissible input horsepower (kW) as a function of the propeller size has been plotted in the diagram, Fig. 3. Curve (a) applies to propellers for tugs, drillships, floating cranes and similar vessels of comparatively high propeller loads. Curve (b), on the other hand, applies to low propeller loads as are generally encountered in free-running vessels, such as passenger ships, ferries, navy vessels etc.

The table at the foot shows the main dimensions (mm), the weights (kg), the moments of inertia (kgm^2), referred to the vertical axis, as well as the oil filling (litres) for all propeller sizes of our present production programme.*) Also see the dimensional sketches in Figs. 4 to 7. A distinction is made between a "single-stage design" with bevel gear unit (Fig. 4) and a "two-stage design" with a spur gear unit preceding the bevel gear unit so that large propellers can use high input speeds.

Two-stage Voith-Schneider Propellers of size 36 and above are equipped with two or three input shafts. With two input shafts, a horizontal or vertical arrangement may be adopted. Fig. 6 shows the horizontal and Fig. 7 the vertical arrangement, which is particularly suited for use with electric motor drive.

Should the tabulated propeller weights exceed the available load-carrying capacities of the shipyard's cranes, the propellers would be delivered as two or three separate subassemblies — casing, rotor casing, blades — and finally assembled on board.

*) The designation of the propeller size indicates the blade orbit diameter and the blade length. For instance, propeller size 24 G/165 has a blade orbit dia. of 24 dm = 2400 mm and a blade length of 165 cm = 1650 mm.



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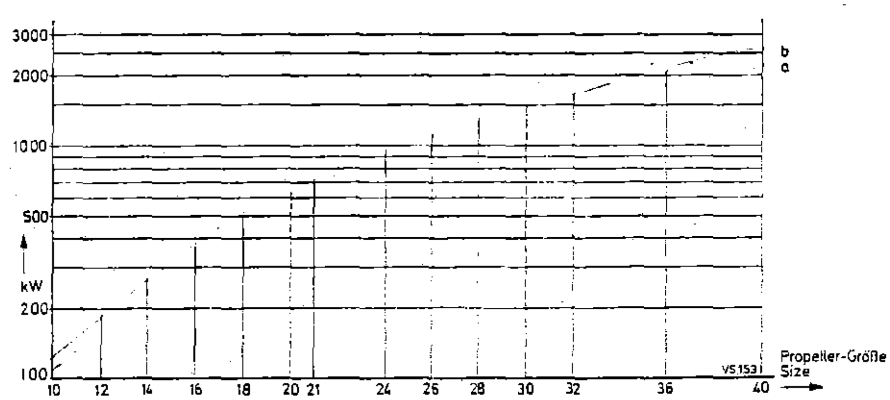

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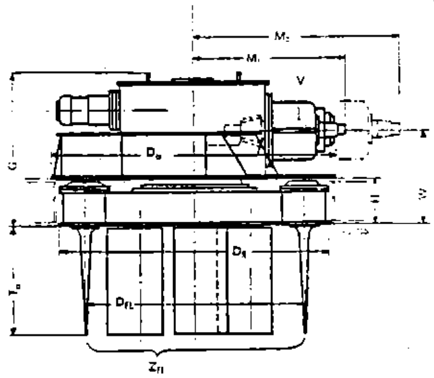
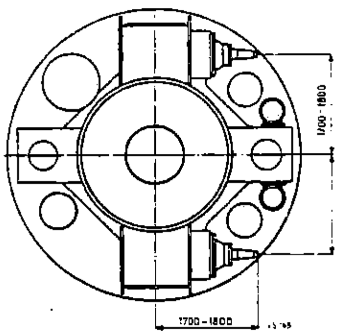
Fig. 3
Relationship between propeller size and input horsepower. Curves a and b: see text.

Prop. Size	D_a mm	D_{FL} mm	D_R mm	T_o mm	Z_{FL}	G mm
8 EG	1106	800	1010	505	4	770
10 EG	1390	1000	1274	653	4	[illegible]
12 EG	1650	1200	1532	756	4	[illegible]
14 EG	1890	1400	1770	893	4	1248
16 G	2145	1600	2021	1007	4	1370
18 G	2405	1800	2263	1156	5	1468
21 G	2800	2100	2625	1356	5	1750
24 G	3160	2400	2970	1655	5	1905
26 G	3360	2600	3170	1655	5	1905
28 G	3680	2800	3480	1855	5	2080
32 G	4220	3200	4000	2006	5	2380
36 G	4750	3600	4490	2262	5	–
40 G	5230	4000	4965	2262	5	–
16 G	2145	1600	2021	1007	4	1370
26 G	3360	2600	3170	1655	5	1770
28 G	3680	2800	3480	1855	5	2000
32 G	4220	3200	4000	2006	5	2300
36 G	4750	3600	4490	2262	5	2700
40 G	5230	4000	4965	2512	5	3300

Dimensions subject to change

VOITH - SCHNEIDER





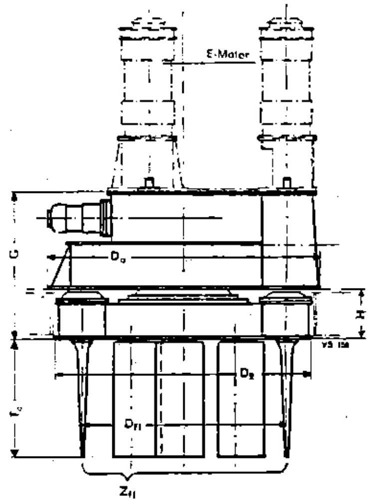


Fig. 4
Dimensional sketch of a single-stage Voith-Schneider Propeller
Z_{fl} = number of blades.

Fig. 5
Dimensional sketch of a two-stage Voith-Schneider Propeller
Z_{fl} = number of blades.
V = preceding gear unit,
shafting offset 250 - 560 mm.

Fig. 6
Plan view of a two-stage Voith-Schneider Propeller with two horizontal input shafts.

Fig. 7
Dimensional sketch of a two-stage Voith-Schneider Propeller with two or three vertical input shafts for electric-motor drive.

W mm	H mm	M mm	M_1 mm	M_2 mm	Weight about kg	Oil filling about litres	Moment of inertia of rotor J kgm²	Gear unit	Propeller input speed*) single-stage	two-stage
300	185	520	–	–	860	80	42,5	single-stage	750-1500	–
[illegible]	242	700	–	–	1660	140	110	single-stage	600-1300	–
[illegible]	296	820	–	–	2600	240	340	single-stage	500-1000	–
550	336	970	–	–	3700	420	650	single-stage	450-900	–
810	383	1130	1345	1785	6000	550	1250	single-stage and two-stage	400-650	650-2000
900	419	1225	1420	1860	8500	850	2250	single-stage and two-stage	350-630	630-1900
1100	500	–	1725	2200	13300	1750	5500	single-stage and two-stage	300-600	600-1700
1230	575	1730	2015	2815	20500	1900	8000	single-stage and two-stage	275-500	650-1600
1230	575	1765	2015	2815	20600	2000	12500	single-stage and two-stage	250-450	600-1450
1330	670	1880	2160	2850	29000	2800	20000	single-stage and two-stage	230-400	500-1450
1550	750	–	2445	3200	40000	4300	41500	single-stage and two-stage	200-300	450-1350
–	–	–	–	–	–	–	–	with 1 or 2 horizontal input shafts		
–	–	–	–	–	–	–	–	consult Voith for design and speeds		
–	383	–	–	–	6700	600	1250	two-stage with 1 vertical input shaft	–	800-1450
–	575	–	–	–	23000	2000	12500	two-stage with 2 vertical input shafts	–	1000-1800
–	670	–	–	–	30000	3000	20000	two-stage with 3 vertical input shafts	–	900-1800
–	750	–	–	–	41000	4500	30000	two-stage with 3 vertical input shafts	–	900-1800
–	900	–	–	–	64000	6800	62500	two-stage with 3 vertical input shafts	–	750-1500
–	1000	–	–	–	80000	10000	125000	two-stage with 3 vertical input shafts	–	750-1200

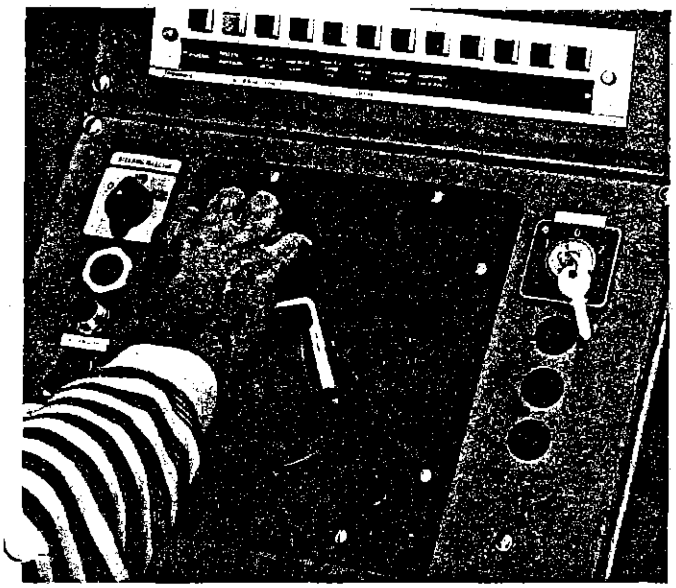
*) The exact speed limits for specific applications must be established in consultation with us

APPENDIX 5.

CONTROLLER

MICROPILOT CONTROL SYSTEM

2 system controls

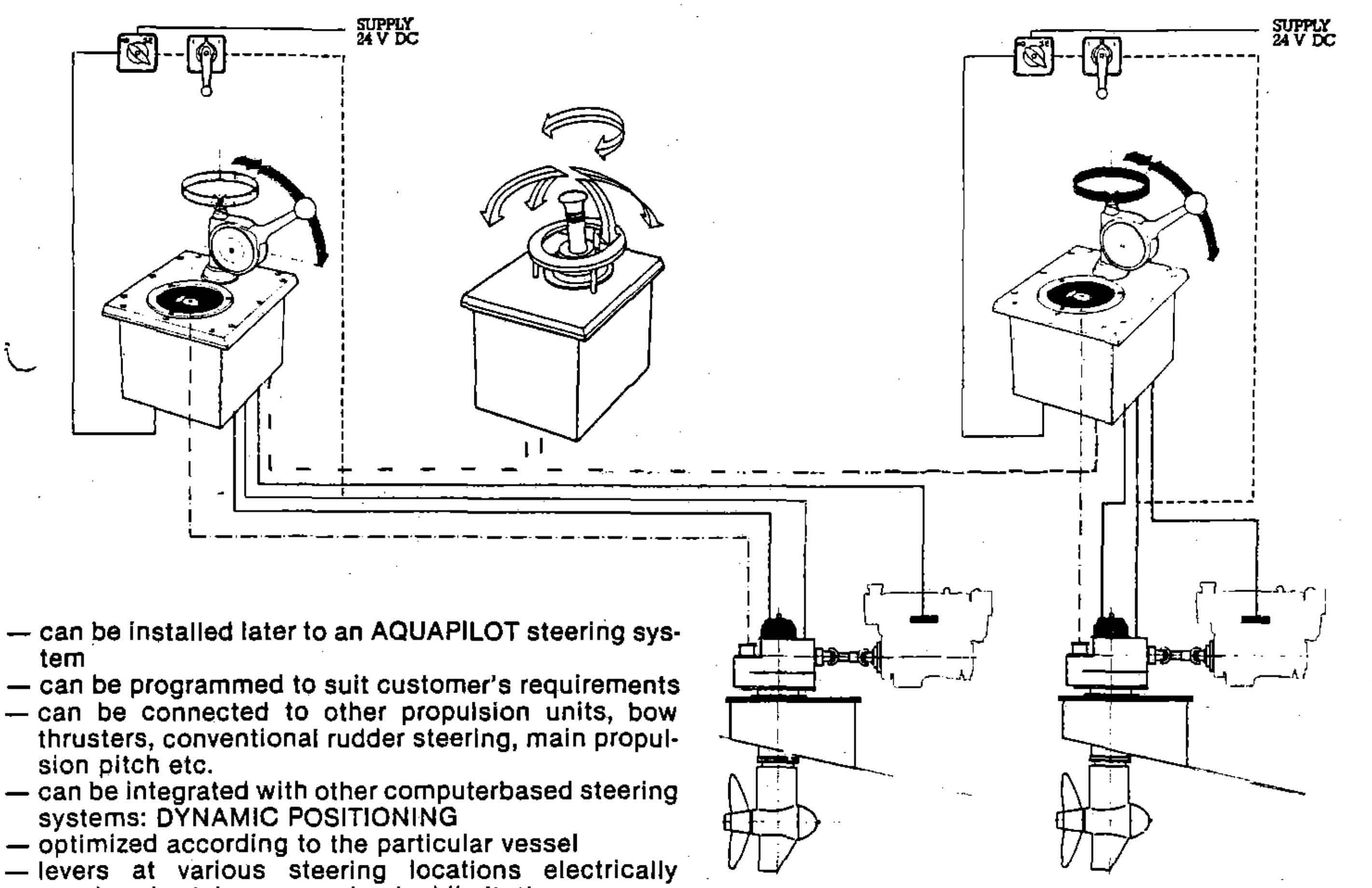


MICROPILOT CONTROL SYSTEM

– integrated microprocessor-based steering system for optimized control of all the vessel's propulsion manoeuvres

System consists of the AQUAPILOT control system components and MICROPILOT steering head(s). For complete control of the vessel's translation and rotation movements, the MICROPILOT has a Joystick and a steering lever or wheel. If only a combination of translation and rotation movements of the vessel are required, the MICROPILOT has only a Joystick.

AQUAMASTER®
NEWS IN BRIEF



— can be installed later to an AQUAPILOT steering system
— can be programmed to suit customer's requirements
— can be connected to other propulsion units, bow thrusters, conventional rudder steering, main propulsion pitch etc.
— can be integrated with other computerbased steering systems: DYNAMIC POSITIONING
— optimized according to the particular vessel
— levers at various steering locations electrically synchronized, i.e. no mechanical limitation
— system range according to customer's requirements, several steering positions, several propulsion units, bow thrusters etc.
— possibility of increasing numbers of steering positions and controlled units at a later date
— possible to change the steering characteristics of vessel at a later date
— autopilot and portable steering unit
— complete reliability, operates on 24 volts d.c. supply