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ENGINEERING AND OPERATIONAL CHARACTERISTICS OF A 210 FOOT MEDIUM ENDURANCE CUTTER CLASS (WMEC)

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6

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16. Abstract

Two U.S. Coast Guard Medium Endurance Cutters (WMEC's) were tested to define baseline characteristics of the 210 foot class. The USCGC VIGOROUS was tested in calm water to obtain speed-power, noise level, machinery vibration levels, and maneuvering data. The results obtained were definitive engine power characteristics and fuel consumption data for double and single engine (controllable pitch) propulsion on the 1000 long ton, medium endurance cutter. Noise levels were measured and related to International Organization for Standardization (ISO) limits.

Rough water testing was performed on USCGC ACTIVE to obtain seakeeping data. Limited results were obtained due to a confused sea state at time of test in four foot significant seas.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10 286

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

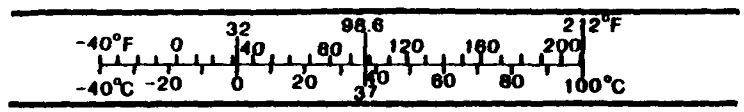


TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont.)

LIST OF TABLES

ACKNOWLEDGEMENTS

Thanks to Robert Desruisseau for supplying the details for the description of the data acquisition system, the accelerometer characteristics, and other instrumentation used in the testing.

ADMINISTRATIVE INFORMATION

The Coast Guard Advanced Marine Vehicles Project (9207) consists of three major elements; Operations Research (9207.1), Ship Test and Demonstration (9207.2) and Hydrodynamics (9207.3). The Advanced Marine Vehicles Project is under the direction of the Marine Vehicle Technology Branch (G-DMT-2) of the Marine Technology Division (G-DMT) in the Office of Research and Development (G-D) in Washington, DC. This technical evaluation of the 210' WMEC was performed as part of the Ship Test and Demonstration element by the Marine Systems Branch of the Coast Guard Research and Development Center in Groton, Connecticut. The Research and Development Center is a Headquarters Unit reporting to the Chief of the Office of Research and Development (G-D).

INTRODUCTION

The U.S. Coast Guard is in the process of evaluating Advanced Marine Vehicles (AMV's), such as hydrofoils, SWATH ships, planing, and surface effect ships, as potential Coast Guard cutters. A necessary part of this process is to quantify the engineering and operational characteristics of AMV's and existing Coast Guard cutters by performing full-scale ship tests so that accurate comparisons can be made. To do so requires testing in calm water to obtain powering and maneuvering data, and in rough water to obtain seakeeping and human response information. The data is collected at sea and then analyzed to obtain the engineering and operational characteristics. This data is then incorporated into the AMV data base for subsequent analyses and comparisons with other vessels.

Full-scale trials offer the opportunity to see first hand the advantages of such operational characteristics as decreased ship motions or increased speed in a seaway. Trials also allow experienced personnel to recognize vessel shortcomings such as reduced range or increased difficulty of maintenance. By performing the same tests on Coast Guard cutters and Advanced Marine Vehicles, data is available to make realistic comparisons of engineering and operational performance.

TEST OBJECTIVE

The objective of this test was to collect baseline information to characterize the 210' class of Medium Endurance Cutters (WMEC's). To fulfill this objective, tests were conducted to quantify the seakeeping, maneuvering and powering characteristics as well as the noise and vibration levels on board a 210' WMEC. It is also desirable to assess the effects of ship motion, noise and vibration upon the crew to fully characterize a vessel. Seasickness and fatigue of the crew were assessed during the trial. In order to obtain enough testing time to perform all of the tests, it was necessary to secure the services of two ships. They were the CGC VIGOROUS (WMEC-627), home port New London, Connecticut, and the CGC ACTIVE (WMEC-618), home port New Castle, New Hampshire.

VESSEL DESCRIPTION

The United States Coast Guard 210' Medium Endurance Cutter (WMEC) is a conventional displacement vessel capable of accomplishing a wide variety of Coast Guard missions. Today they are used primarily in law enforcement and search and rescue. A 210' is capable of carrying out two week patrols without reprovisioning. It has 360° pilot house visibility, a helicopter flight deck, refueling facilities and is capable of towing other vessels up to 10,000 tons. A total of 16 of these cutters were built from 1963-69, all of which are still in active service. A list of particulars and profile drawing appear in Table 1 and Figure 1, respectively.

The Coast Guard Cutter ACTIVE (WMEC-618) was originally built with a combined diesel and gas turbine (CODAG) plant. In 1975 the gas turbines were removed and the existing Cooper Bessemer diesels were modified to produce 2500 BHP each. The VIGOROUS (WMEC-627) has ALCO diesels for main propulsion.

INSTRUMENTATION

The heart of the shipboard instrumentation system is a 14-channel analog tape recorder. The output signals from the Ship Motion Package, horsepower meters, accelerometers and other instruments are routed to the recorder for continuous taping during tests. A block diagram of the Data Acquisition System is in Appendix A, page A-2.

The instrumentation system includes a directional ENDECO 956 Wave Track buoy deployed for seakeeping tests so that actual sea conditions can be measured. The ENDECO receiver converts wave height and buoy tilt signals into an 8-bit binary code which is transmitted to the vessel where it is processed by an Otrona Attache microcomputer. Significant wave height and a wave energy direction vs frequency plot (see Figure 2A) are produced on board. The wave data is also presented as a three-dimensional plot with frequency converted to wave period as seen in Figure 2B.

Other instruments are read and recorded manually during testing; they include a sound level meter, fuel flow meters, and a human response meter. A description of the transducers, associated instruments and their characteristics, as well as an engine room accelerometer placement diagram, is listed in Appendix A.

TEST DESCRIPTION

The intent of this technical evaluation was to quantify the engineering and operational characteristics of the 210' WMEC (Reliance Class) Coast Guard cutter; accordingly, information was required in the following areas:

- Seakeeping Ability - Ship motion in waves and the ranges of seasickness and fatigue for humans in response to heave.

- Maneuverability - Turning rate (spiral test) and rudder response (zig-zag maneuver)

- Speed, Power, and Fuel Consumption

- Noise Levels in Living and Machinery Spaces

- Structure and Machinery Vibration Levels

TABLE 1

LIST OF PARTICULARS

Length, Overall	210' 6"
Length, Design Waterline	200' 0"
Beam, Extreme	34' 0"
Draft, Maximum	10' 6"
Displacement, Light	769 tons
Displacement, Full Load	997 tons
Main Engines	2 ea. 2500 hp Diesels Cooper-Bessemer (WMEC 615-619) ALCO 251B (remainder of class)
Propellers	2 ea. 4-bladed 7'6" diameter controllable pitch
Generator	2 ea. 200 kw diesel ships service generators 1 ea. 100 kw diesel emergency generators
Fuel Capacity	47,280 gallons (marine diesel)
Fresh Water Capacity	8,240 gallons
JP-5 Capacity	2,260 gallons
Lube Oil Capacity	1,091 gallons
Full Speed	18 knots, Range 4030 nm
Range at 7 knots (single engine)	15,000 nm
Range at 8 knots (2 engine)	7570 nm

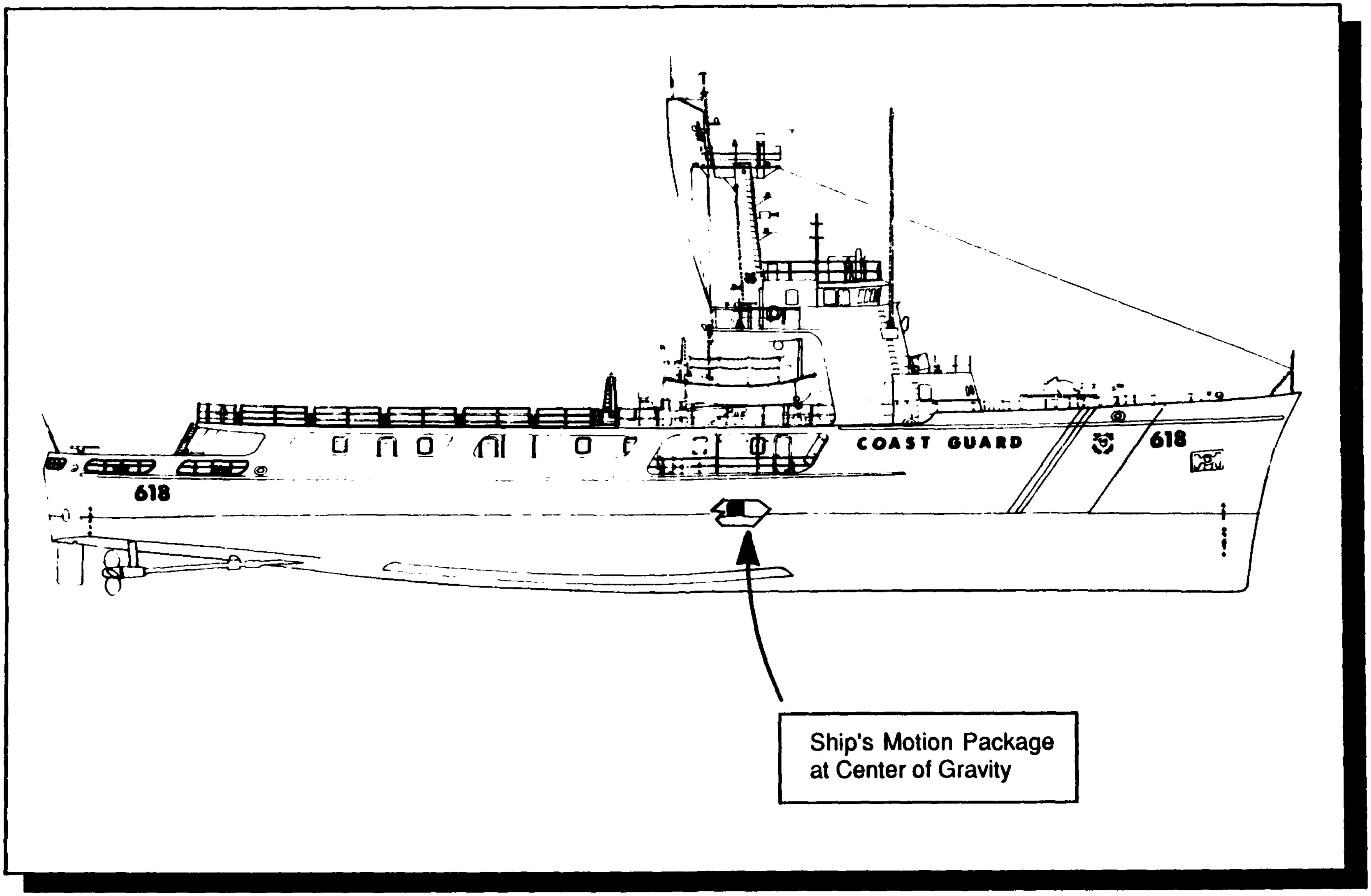


Figure 1. USCGC Active (210ft - WMEC 618)

Quick-look Plot of Frequency/Direction Spectrum
(Entries are scaled linearly from 0 to 50)
Peak value corresponds to spectral density of .081 (FT-SQ/HZ•DEG)
April 25, 1984

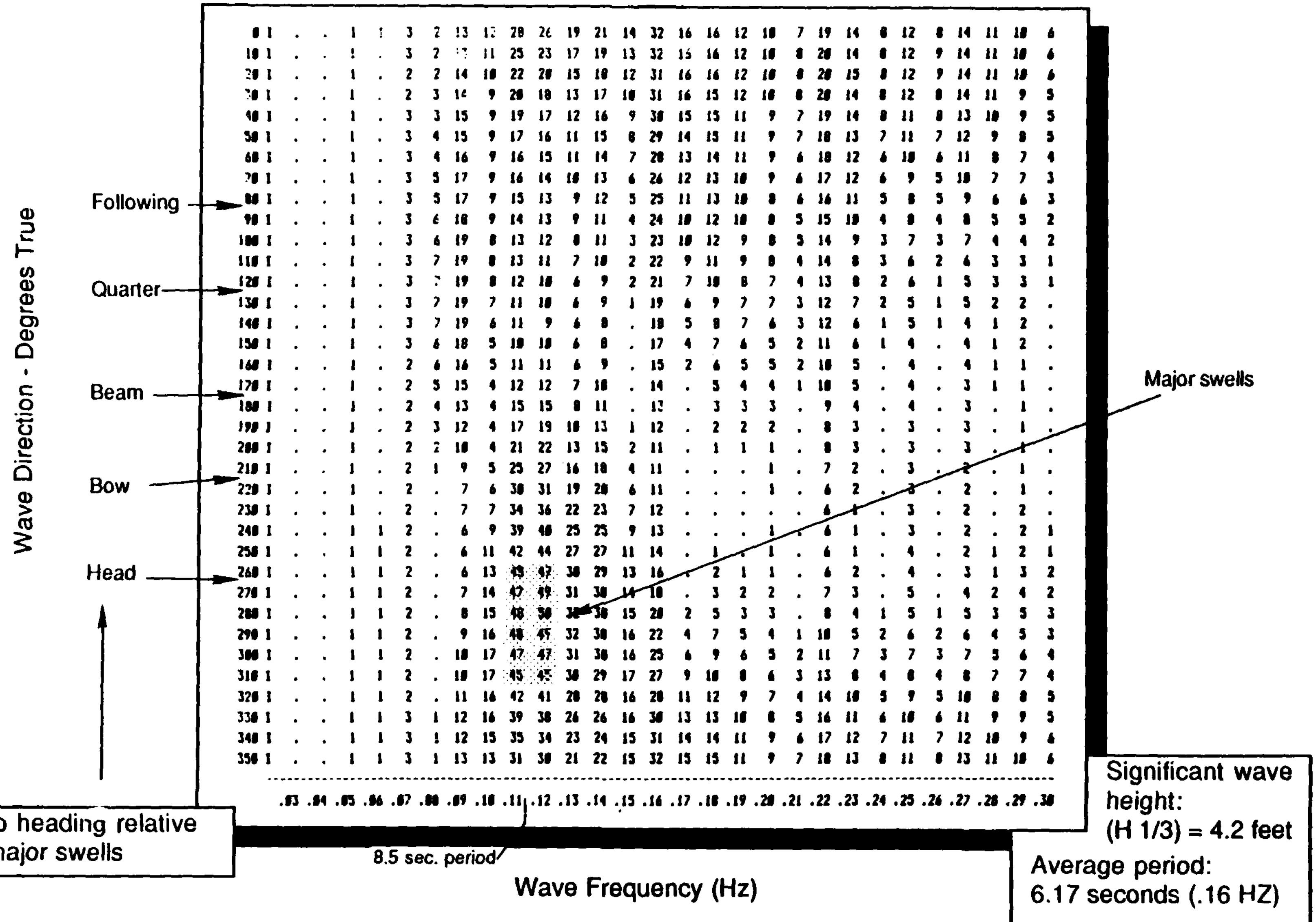
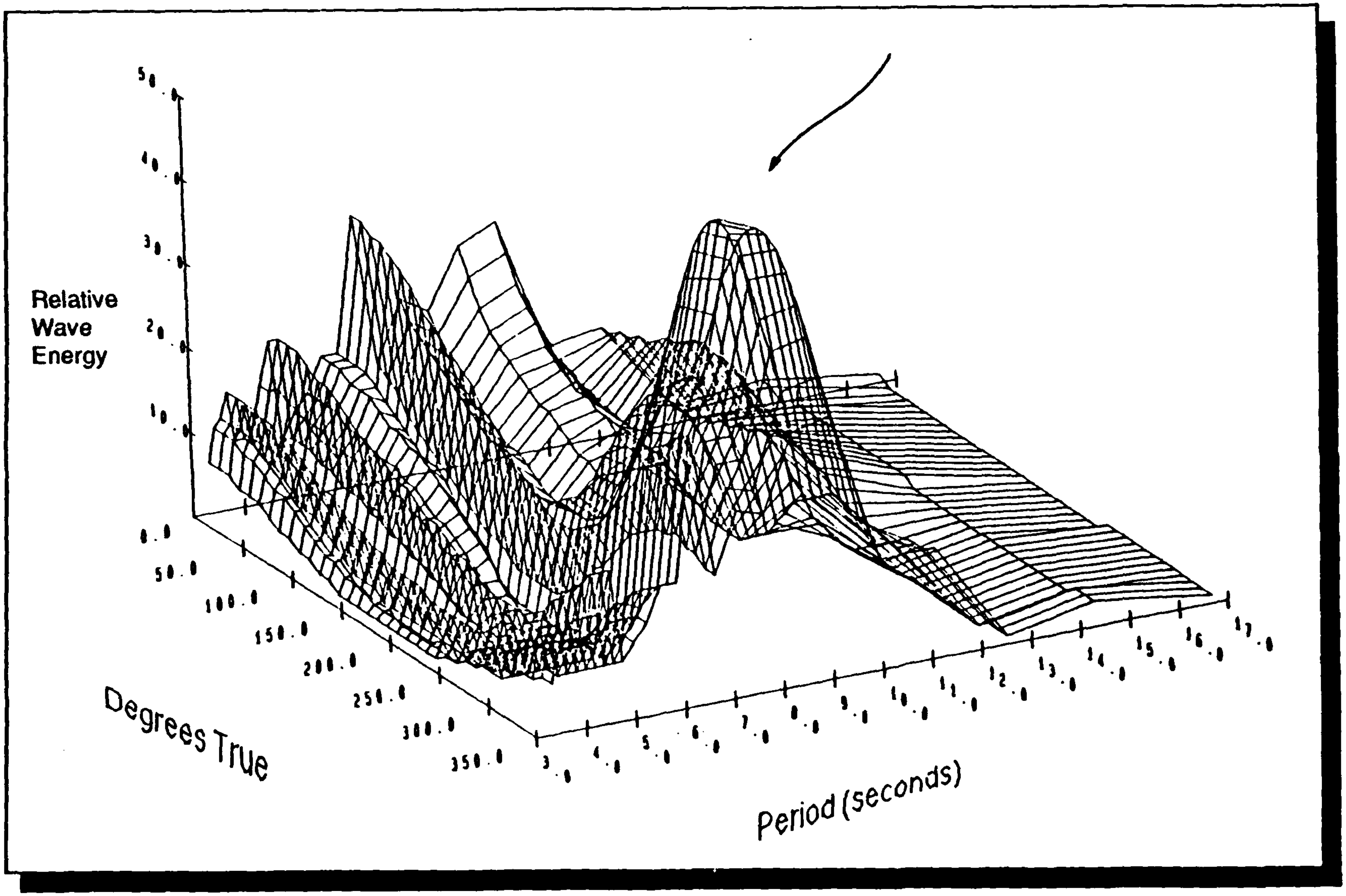


Figure 2A. Wave Energy Distribution

Peak value corresponds to spectral density of 0.081 ($ft^2/Hz*Deg$)



Significant Wave Height (H 1/3) = 4.2 feet

Figure 2B. 3-d Wave Energy Plot

To obtain this information a standard set of tests, shown below, were scheduled. These tests are described in detail in the General Test Plan (GTP) (Reference 1).

Description	GTP Test Number
Principal Characteristics	1
Speed vs Power	3
Fuel Consumption & Endurance	4
Maneuverability - Spiral Test	8
Maneuverability - Zig-Zag Maneuver	9
Motion in Waves	13
Hull Vibrations Level	23
Noise Level	24
Seakeeping Ability - Physiological	37

All tests were conducted in accordance with the General Test Plan with minor exceptions. During the Spiral Test at 12 knots, the rudder angle was limited to 10 degrees by the Commanding Officer of the VIGOROUS to prevent excessive heeling of the vessel.

The trials were run on a "not to interfere with operational commitments" basis. The calm water tests were run on the CGC VIGOROUS approximately 200 nm south of Cape Hatteras while it was enroute from New London, Connecticut, to Miami, Florida, on 3 and 4 April 1984. Seas ranged between calm and one foot on these two days. Detailed seakeeping tests, however, were not performed on VIGOROUS due to operational commitments. Ship motions with 5-6 foot bow quartering seas were recorded while transiting to Florida, however, a wave buoy was not deployed.

The main seakeeping tests were performed on 25 April 1984 aboard the CGC ACTIVE approximately 25 miles east of Portsmouth, New Hampshire. These tests followed a large "northeaster" which had been in the area for three days, and resulted in 8-10 foot swells from the east earlier in the day. Due to a search and rescue mission by the ACTIVE (involving a disabled fishing boat, 150 miles from Portsmouth), it was not possible to perform the tests until after a sharp cold front had passed and the winds shifted which reduced the seas to four feet. As seen in Figure 2B, the seas were multidirectional, or somewhat "confused", at the time.

DATA REDUCTION

The raw data was collected at sea for motion in waves from a calibrated ship motion package. Data reduction back in the lab was required to convert the voltage readings recorded on an analog tape recorder to engineering units. Applicable statistics were computed with the use of a computer and analog to digital converter (voltmeter). Machinery and structureborne vibrations were analyzed by utilizing a Hewlett Packard 5420A Digital Signal Analyzer to process the recorded accelerometer signals.

Some data, such as shaft rpm, horsepower and fuel flow were recorded manually directly from the instruments at the time of the test. Ship speed was measured by the vessel's pitotmeter log. Noise levels were read directly with a sound level recorder at various locations in the ship. The seaway data was transmitted from the ENDECO buoy and received on board the ACTIVE. It was then reduced using ENDECO's software on the OTRONA computer to produce the wave energy frequency-direction distribution, Figure 2A. The majority of the raw data, however, was reduced and processed at the Research and Development Center after the completion of the trial.

Seakeeping tests aboard the ACTIVE were conducted in four foot significant waves at shipheadings relative to the major swell energy coming from 260°T as seen in Figure 2A. For each of the five legs (head, bow, beam, quarter and following seas) of the seakeeping runs, ship motion (roll, pitch and heave) were averaged over 20 to 30 minute periods. The average highest one third (H (1/3)) and average highest one tenth (H (1/10)) single amplitudes were computed by the R&D Center software programs GENSES and GENPEAK.

The GENSES program runs on a Hewlett-Packard (HP) 9835B computer. Up to 20 channels of analog data recorded on the Racal tape recorder(s) are digitized with the HP data acquisiton control unit and HP digital voltmeter. The GENPEAK program then searches the digital file for peaks, records all peaks exceeding a defined limit (e.g., one degree of roll above or below the mean signal level) and then sorts these peaks from high to low. Subsequently, the H (1/10) and H (1/3) values are computed.

ANALYSIS AND RESULTS

ROUGH WATER

Motions - Polar plots of roll, pitch, and heave are presented in Figures 3, 4, and 5. These plots show two sets of CGC ACTIVE data, average 1/3 highest, and average 1/10 highest single amplitude excursion of roll, pitch and heave in 4.2 foot significant wave height.

Figure 2A depicts a frequency/direction spectrum and relative wave energy for the confused sea state encountered during rough water seakeeping tests. The sea state may be roughly characterized as a mature, decaying, 3-day swell from the east (approximately 8.5 second period) being subdued by newly formed short period (higher frequency) and building wind-blown waves from the west (approximately 20 knots).

These wind-driven waves are so diverse in direction that they preclude the calculation of ship Response Amplitude Operators (RAO's) for heave, roll and pitch. According to Reference 2, a unidirectional sea state is required in order to analytically calculate a useable RAO. Ship motions are usually diminished when testing in a multidirectional sea as compared to tests conducted in a unidirectional sea of the same magnitude.

Figure 3 shows that bow quartering seas produced the most severe roll motions. This has been observed in other ship techevals such as the USCGC MALLOW, a 180' buoy tender. The results of pitch response in Figure 4 are quite unusual in that "beam seas" produced the most severe pitch amplitudes. This is attributed to the confused seas which were so diverse in direction that some waves were still encountered on the ship's head and bow quarters when the major swells were off the "beam" as seen in Figure 2A.

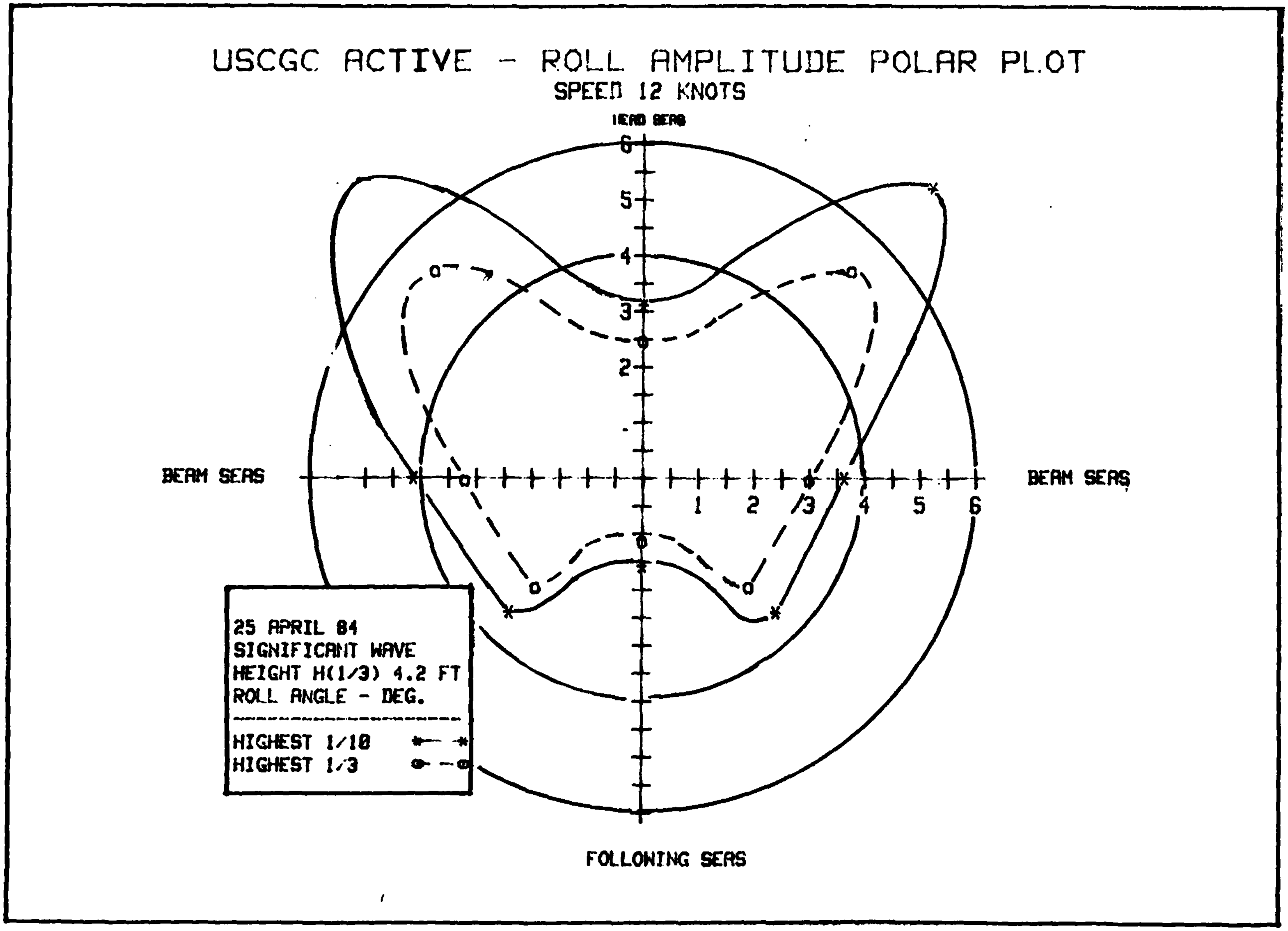


FIGURE 3. ROLL AMPLITUDE POLAR PLOT, 12 KNOTS

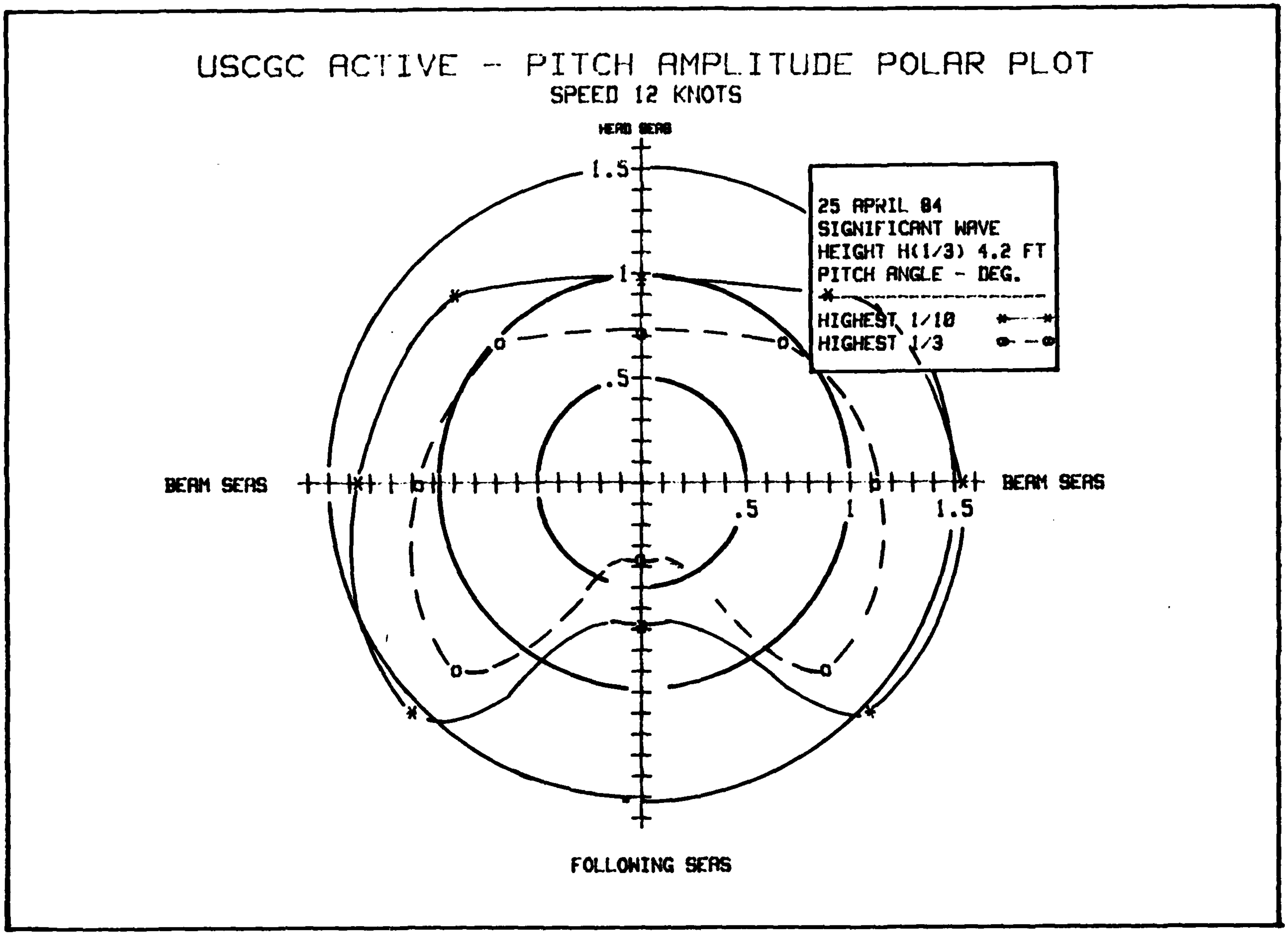


FIGURE 4. PITCH AMPLITUDE POLAR PLOT, 12 KNOTS

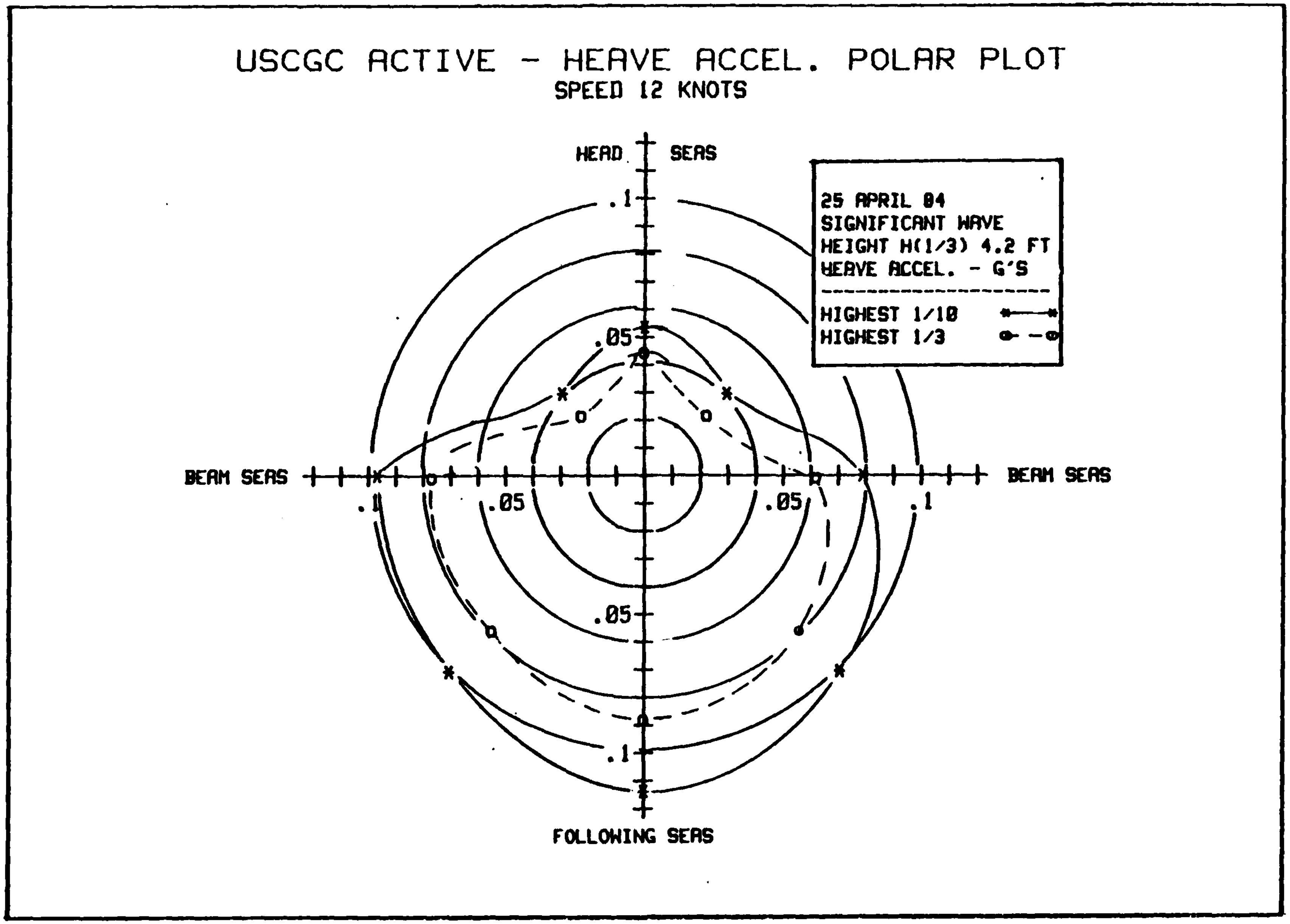


FIGURE 5. HEAVE ACCELERATION POLAR PLOT, 12 KNOTS - CGC ACTIVE

The ACTIVE was observed for a period of twelve hours making 10-12 knots in 8-10 foot seas without slamming or pitching excessively. During turns involving bow, stern quartering seas, and beam seas, pronounced amplification of both pitch and roll motions occurred during maneuvering to engage and tow a disabled commercial fishing boat.

Figure 5 shows larger values in heave acceleration in following, stern quarter, and beam seas than for head seas and bow quartering seas. This condition is not the normal pattern for vertical heave. It is noted that the maximum level of acceleration (0.11 g) is small. The frequency of wave encounters may account for the uncharacteristic high heave response in following seas. If the wave encounters are close to the natural heave frequency of the vessel, then vertical motions of the ship are amplified. This may have been the case during following seas runs at 080°T. Although the major swells were at the stern, the vessel was still heading into significant waves during the "following" sea run at .09, .11, .16 and 22 Hz or 11, 9, 6.3 and 4.5 second periods. This can be seen in Figure 2A. The wave power spectral density table is presented in Appendix B. To more fully characterize the ship motions of the WMEC it is necessary to perform the seakeeping tests in unidirectional waves. Only very general comparisons with other vessels can be made using the data from this test. Specific comparisons of the magnitude of motions of ships tested in different sea states can only be made if the motions are measured in unidirectional waves and appropriate roll, pitch and heave RAO's are calculated.

Some seakeeping data was collected on the VIGOROUS. There was not enough time to place a wave buoy over the side because of operational commitments. However, 5-6 foot swells were estimated visually. Roll, pitch, and heave data were measured at the center of gravity during a 12 knot transit with 5-6 foot swells of the bow quarter. This seakeeping information is presented in Table 2.

TABLE 2

USCGC VIGOROUS SEAKEEPING
(5-6 Foot Seas Off Bow Quarter)
Speed 12 Knots

Single Amplitude	Highest Peak	H (1/10)	H (1/3)
Roll (Deg)	10.2	7.8	6.3
Pitch (Deg)	4.9	3.6	2.8
Heave (g's)	0.37	0.25	0.20

Human Response - Motion Sickness - Table 3 catalogs the findings of measurement of human response to vertical heave on the USCGC VIGOROUS as it made its way into Northern Florida coastal water in a springtime storm. The measurement made was for severe discomfort due to motion sickness and illustrates well the capability of International Organization Standard 2631 (ISO) to predict human body reaction to low frequency whole body motion on board ship. The main relative indication of discomfort is the last row. This

TABLE 3

USCGC VIGOROUS
HUMAN RESPONSE - MOTION SICKNESS

Measured by Bruel & Kjaer Human Response Vibration Meter
Using Vertical Accelerations
4 April 1985

Ship Heading 222°
Wind 145° @ 27 knots
Wind waves 170°, 4 ft.

Speed 12.5 knots
Swell 150°, 5-6 ft.

Sensing Location	Mess Deck	CG (E.O. Stateroom)	Wardroom	Forward Berthing 1-52-1	C.O. Cabin	Bridge
Start Time	13:26	12:25	13:02	13:59	14:38	14:16
End Time	13:38	12:37	13:14	14:11	15:50	14:28
Elapsed Time (min)	12	12	12	12	12	12
Equivalent Exposure (%) of Severe Discomfort Limit Reached During Elapsed Time	20	48	46	154	99	101
Peak Equiv. Accel. (dB)	127.0	132.5	130.5	134.0	133.0	137.0
Peak Equiv. Accel. (m/s2)	2.3	4.2	3.40	5.0	4.25	7.1
Peak Equiv. Accel. (g's)	.23	.43	.35	.51	.43	.72
LEQ Equiv. Accel. (dB)	116.5	120.5	120.0	125.5	123.0	123.0
LEQ Equiv. Accel. (m/s2)	0.68	1.05	1.00	1.92	1.85	1.185
LEQ Equiv. Accel. (g's)	.07	.11	.10	.20	.19	.12
Time to reach 100% Severe Discomfort Limit (min.)	56	25	25	9.3	12.7	12.8

is the time it takes to reach 100% of the most severe ISO sea sickness standard "severe discomfort limit". The mess deck was easily the best location to ride out the storm. Approximately half the crew was seasick during this test period.

Data for Tables 2 and 3 was collected simultaneously. Note that accelerations measured at the center of gravity (CG) with the B&K meter (Table 3) are lower than H (1/3) heave measured by the ship motion package (Table 2), i.e., 0.11 vs 0.20 g's. This is because the Level of Equivalent Exposure (LEQ) reading is a weighted mean. The weighting filter configured to meet ISO standards for seasickness measurements tends to lower the values. Mean is always lower than the average highest 1/3 values which were presented from the motion package. It can be seen from Table 3 that heave at the bridge, Commanding Officer's cabin, and forward berthing is approximately twice that experienced at the center of gravity.

CALM WATER

Maneuverability - Spiral and Zig-Zag Maneuvers - The Spiral Test Maneuver is designed to measure the basic steering ability of the ship. This is accomplished by turning the ship's rudder from 20° right to 20° left (and back to 20° right) in small, successive rudder angle changes, each held long enough to determine steady turning rates at each rudder angle (see Appendix B, Table B-3). Good stability is present when there is a lack of hysteresis (flats) on the curve of rudder angle and yaw rate, since flats would indicate that a whole range of turning rates would be available at some rudder angle and would not necessarily be repeatable at the same value of rudder angle approaching zero angle from port or starboard side. Curves of Yaw Rate vs Rudder Angle (spiral plots) are presented in Figures 6 and 7, for 6 and 12 knots, respectively. As expected, the turning rate is nearly twice as great for 6 knots as 12 knots for the same amount of rudder angle. The 6 knot data shows almost no hysteresis while the 12 knot case shows a perceptable amount. During the 12 knot spiral test the Commanding Officer of the VIGOROUS limited the rudder angle to 10 degrees to prevent the vessel from heeling to an unacceptable angle. The VIGOROUS exhibited very good steering control at rudder angles close to zero degrees. Maneuvering data is also presented in table form in Appendix B.

The results of the zig-zag maneuver are indicators of the ability of a ship's rudder(s) to control the vessel. Factors such as speed of the rudder control system and rudder effectiveness, as well as stability of the ship come into play. A standard procedure outlined as follows was utilized.

a. The ship is steadied on a straight course at a preselected speed for about one minute. Once a speed is established, the power plant controls are not changed throughout the maneuver.

b. Rudder angle is deflected at maximum rate to the left 20 degrees and held until the ship responds 20 degrees to the left of base course.

c. At this point, the rudder is shifted 40 degrees, to right 20 degrees rudder and held until the ship responds in heading 20 degrees to the right of base course. This completes the overshoot test.

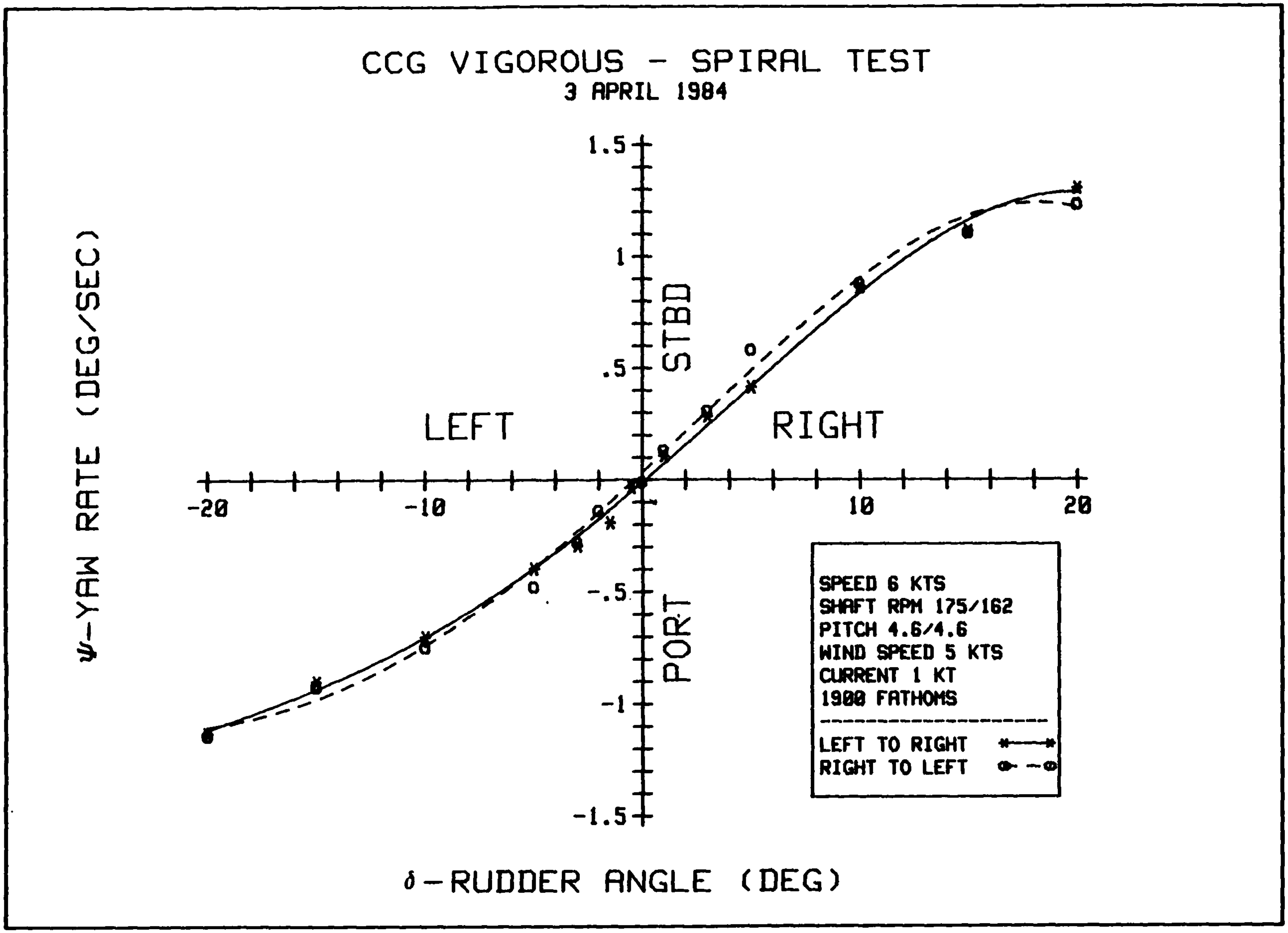


FIGURE 6. SPIRAL TESTS, 6 KNOTS

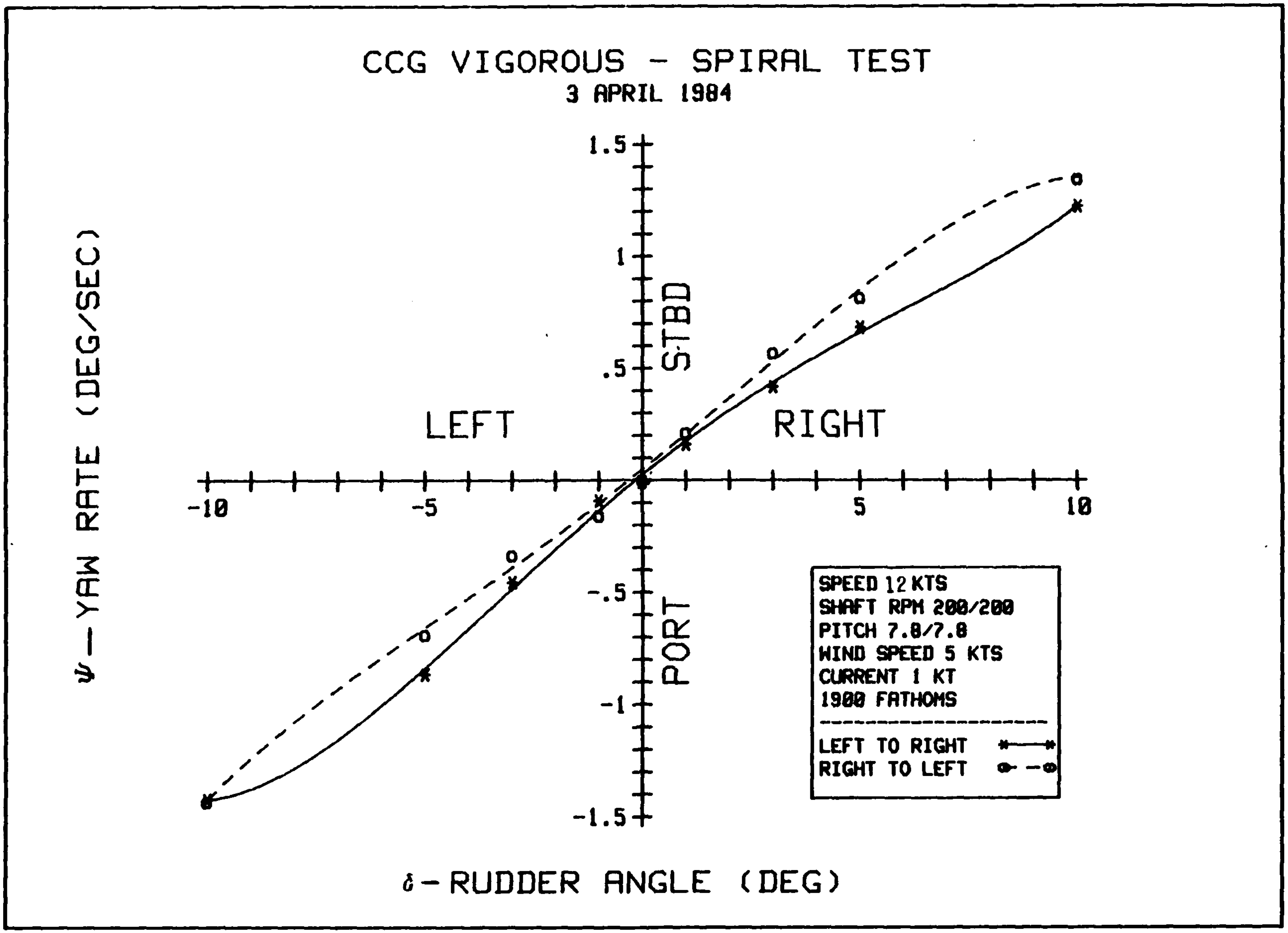


FIGURE 7. SPIRAL TESTS, 12 KNOTS

d. If a zig-zag test is to be completed, again the rudder is shifted 40 degrees, to left 20 degrees rudder. This cycle is repeated once more.

Overshoot yaw angle is an indication of the amount of anticipation required of a helmsman while operating in restricted waters. The time for the ship to react to a 20 degree rudder change starting from rudder amidship on a base course and ending with the ship's yaw angle changing 20 degrees, is an indicator of rudder effectiveness. Another indicator of rudder effectiveness is the "period". This is the time it takes vessels to cycle through two course changes. In these tests, it is the time starting with the first yaw angle reaching 20 degrees to port of base course cycling through 20 degrees to starboard of base course and ending when yaw angle again reaches 20 degrees to port, as depicted in Figures 8 and 9.

The effectiveness of the steering and rudder system in turning is measured by the time to reach second execute, and overshoot in the zig-zag test. The WMEC has a more than adequate steering system and good rudder control. The zig-zag maneuver data for 4 and 10 knots is presented in Figures 8 and 9. The overshoot is greater and the responsiveness is faster for the higher speed.

From an operational point of view, the most important measure of rudder performance is the Time to Second Execute. This is the time, after the rudder has been set to a given angle, for the ship to come to the same yaw angle (20 degrees in this test). The helmsman can use this information to anticipate overshoot when steadying upon a new course. All maneuverability tests were conducted with one steering pump engaged, which is standard for open ocean operations. Two-pump operation will improve rudder response and is usually reserved for restricted water operations such as docking maneuvers.

Powering - The Speed vs Power relationship for two-engine operation is presented in Figure 10. The data for port and starboard shafts have been plotted individually to show the close matching of power on the two shafts over the full range, and as total combined shaft power. Furthermore, since one of the engines had its piston rings replaced within approximately 35 engine hours of running the ship test, engine speed was kept approximately 10% below the rated speed of 1000 rpm (approximately 278 shaft rpm). Consequently, the speed-power curve does not exhibit full power engine capability.

Figure 11 shows single starboard engine operation with the port engine freewheeling*. The plot of two-engine operation is superimposed on the figure to show the "new" engine operation curve, as the single engine assumes the load previously shared by both engines.

Figure 12 depicts the speed-rpm relationship for single and two-engine operation. The Fuel Consumption section of this report has a full discussion of fuel efficiency vs speed for both single and two engine operation. Power data is presented in Appendix B.

Fuel Consumption - Fuel measurement is crucial to interpreting the speed-power relationship. Figure 13 illustrates the loss of low specific fuel consumption when the engines are utilized at speeds below the design point of 1000 engine rpm. This loss is due to the variable displacement of the turbo

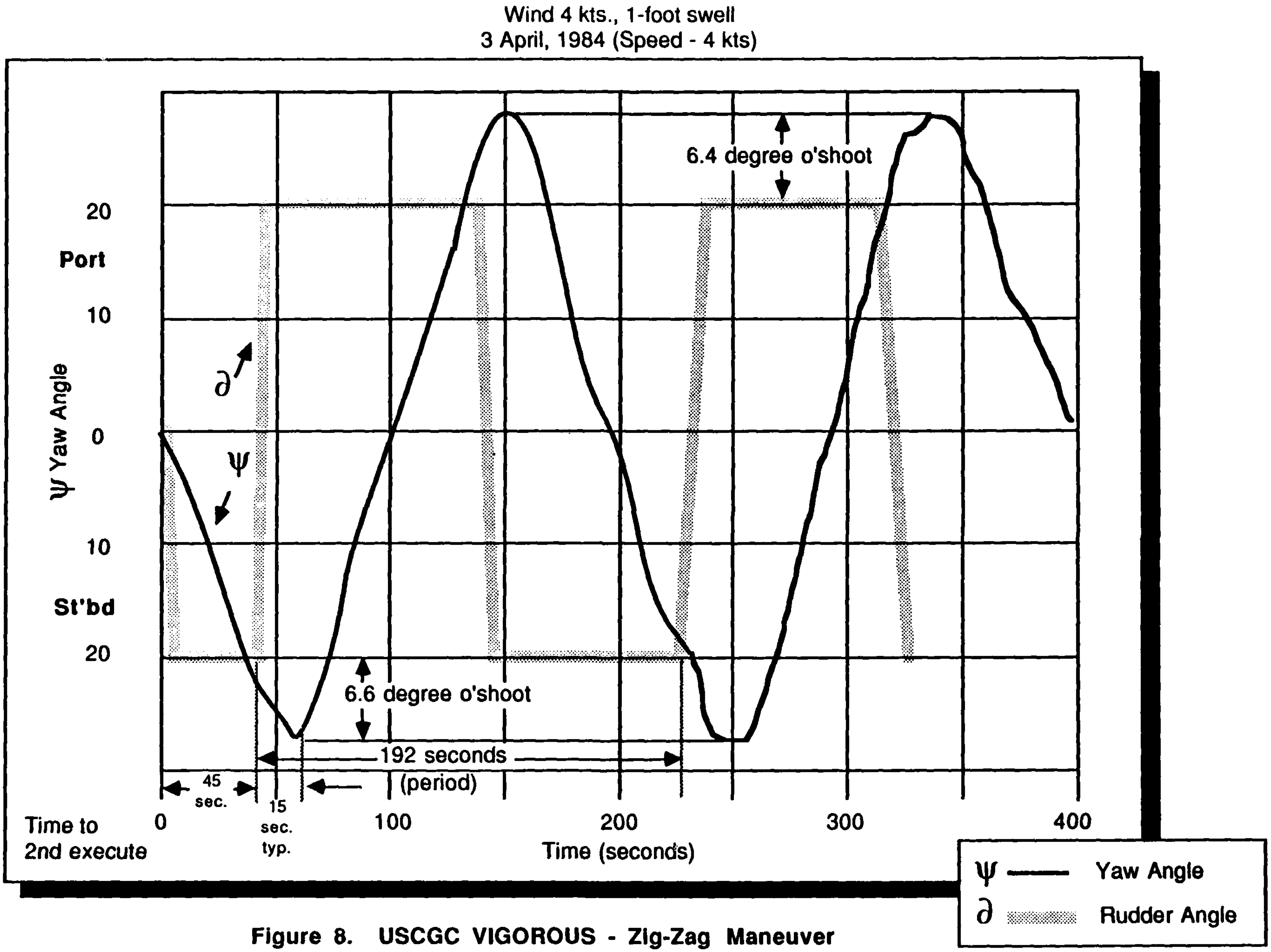


Figure 8. USCGC VIGOROUS - Zig-Zag Maneuver

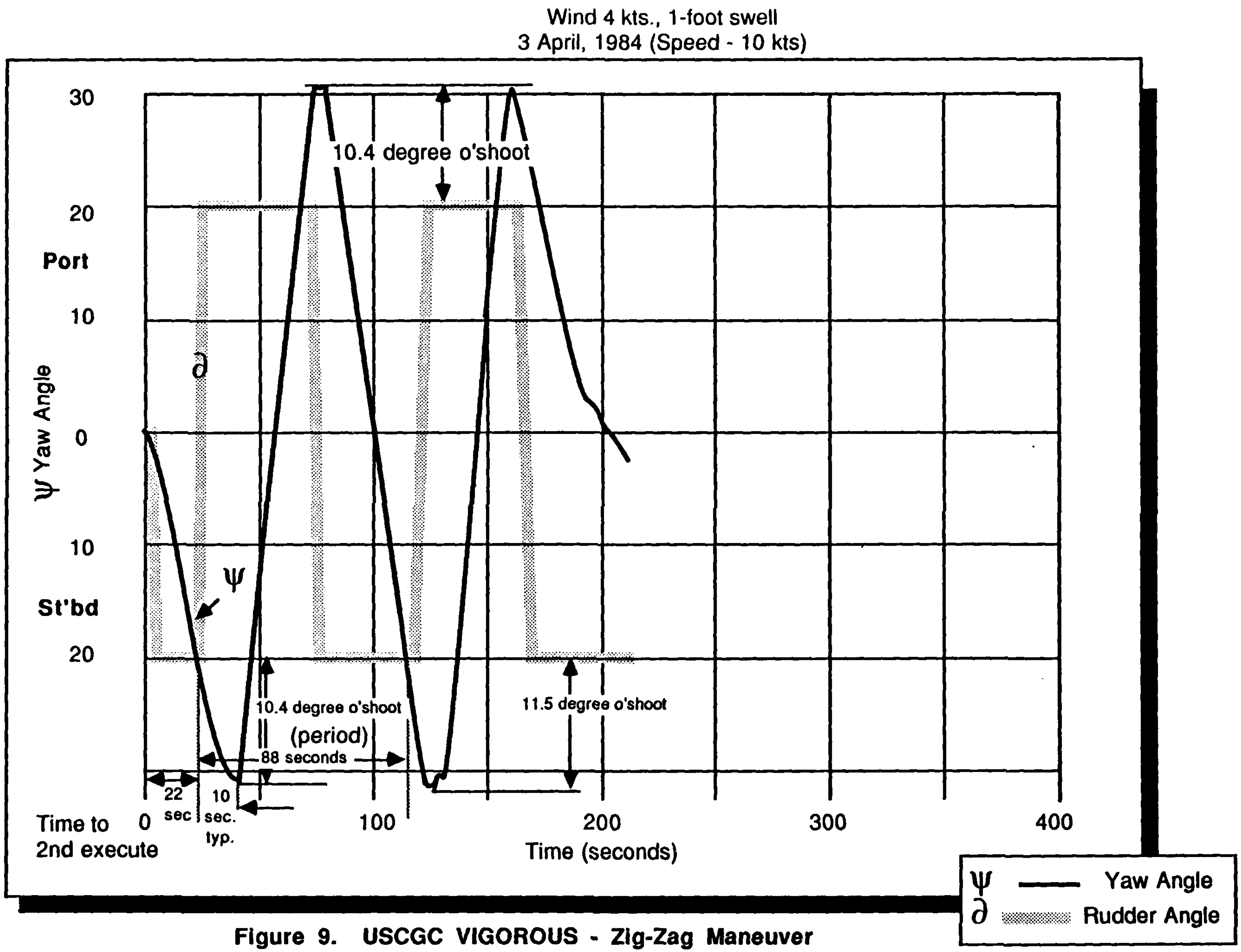


Figure 9. USCGC VIGOROUS - Zig-Zag Maneuver

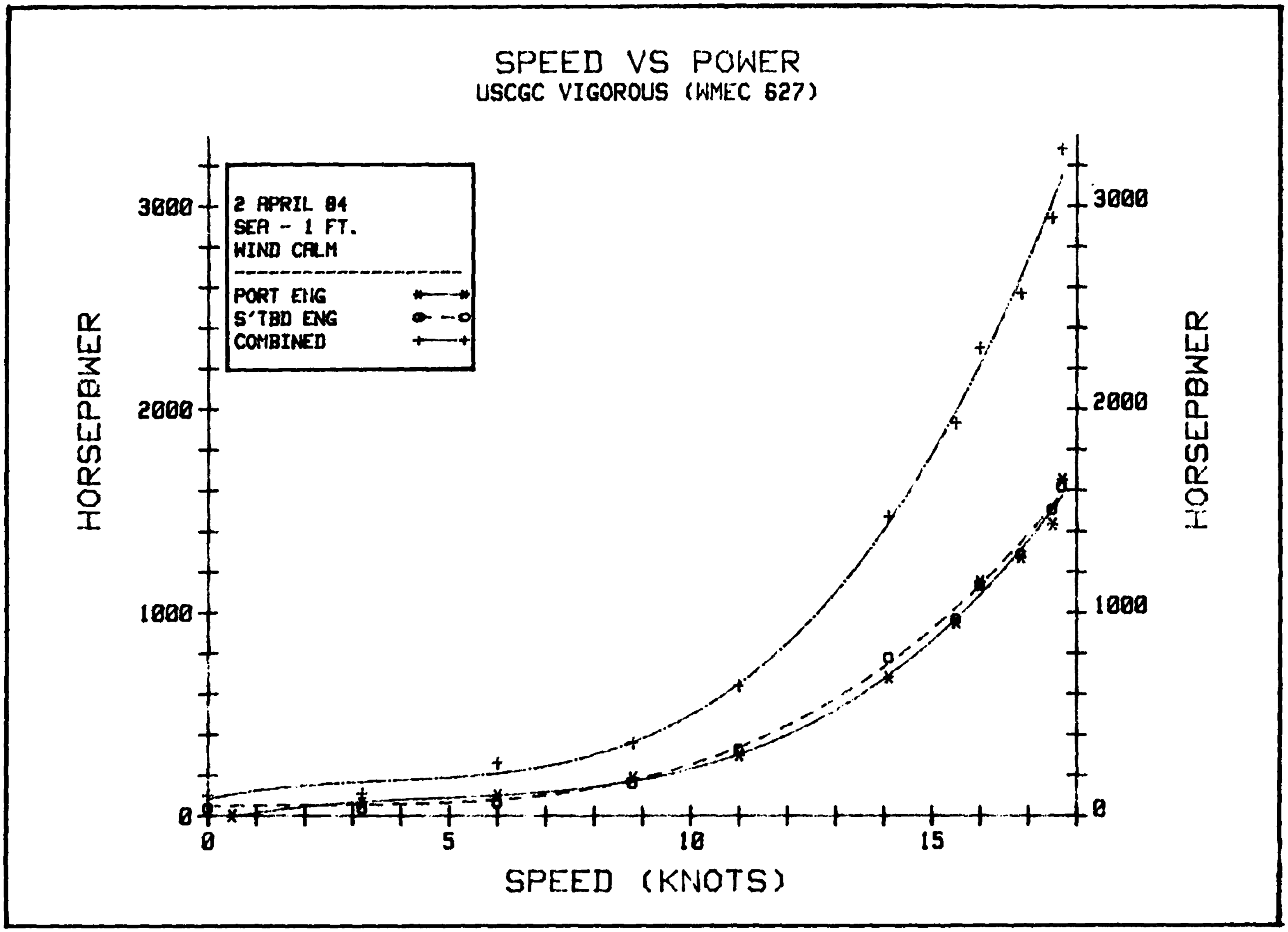


FIGURE 10. SPEED vs POWER

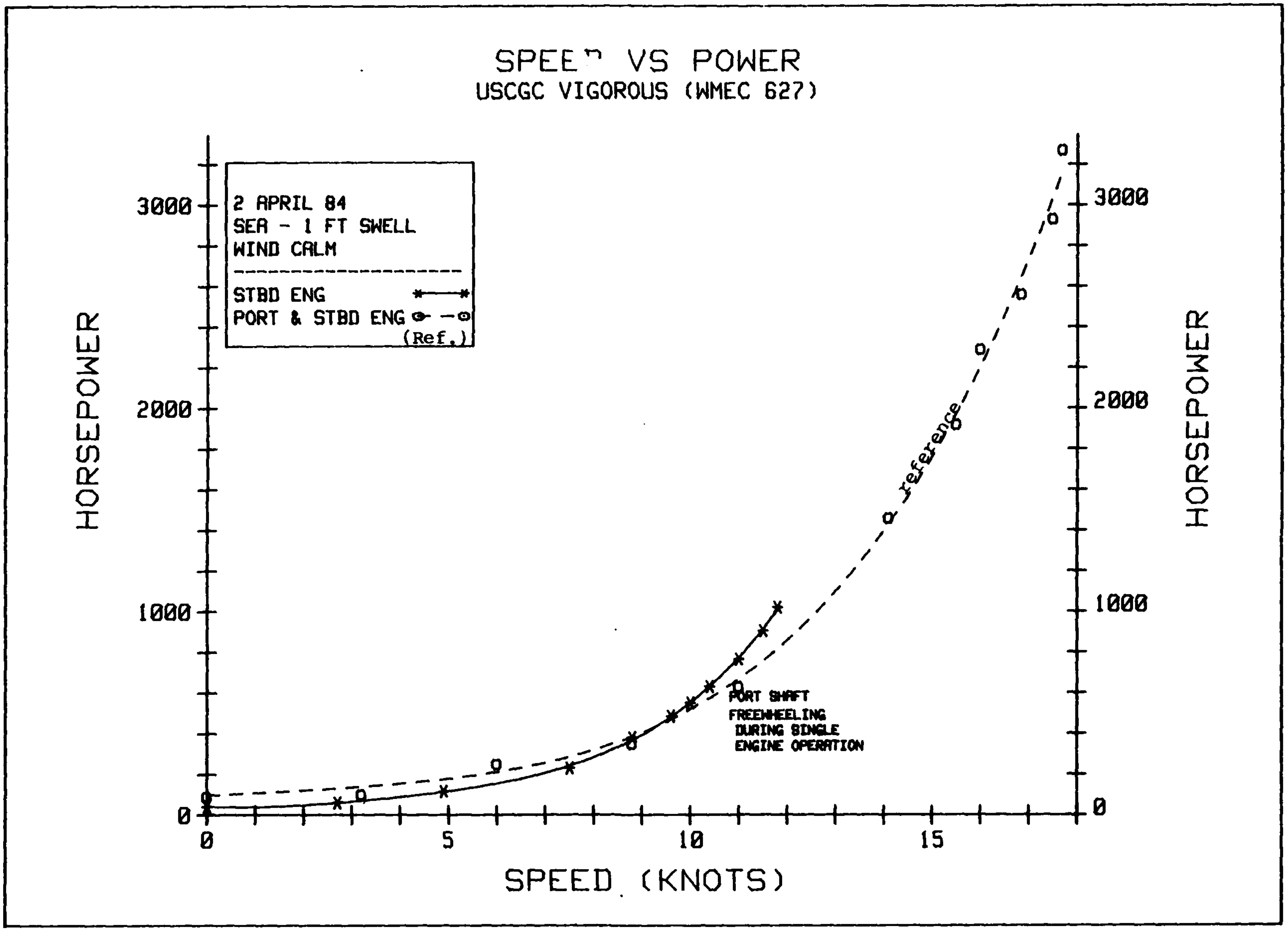


FIGURE 11. SPEED vs POWER, ONE ENGINE

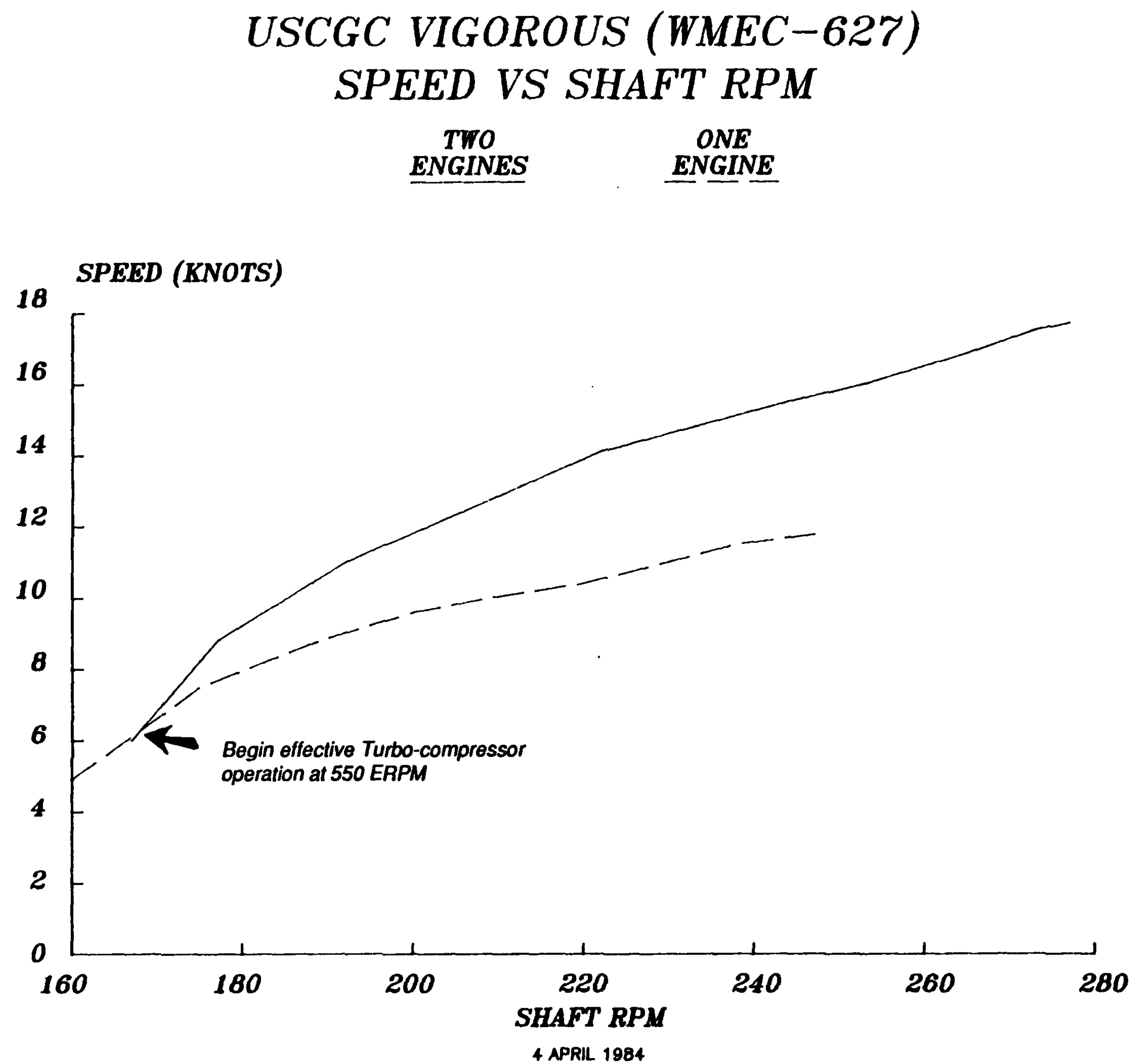


Figure 12. Speed vs Shaft RPM

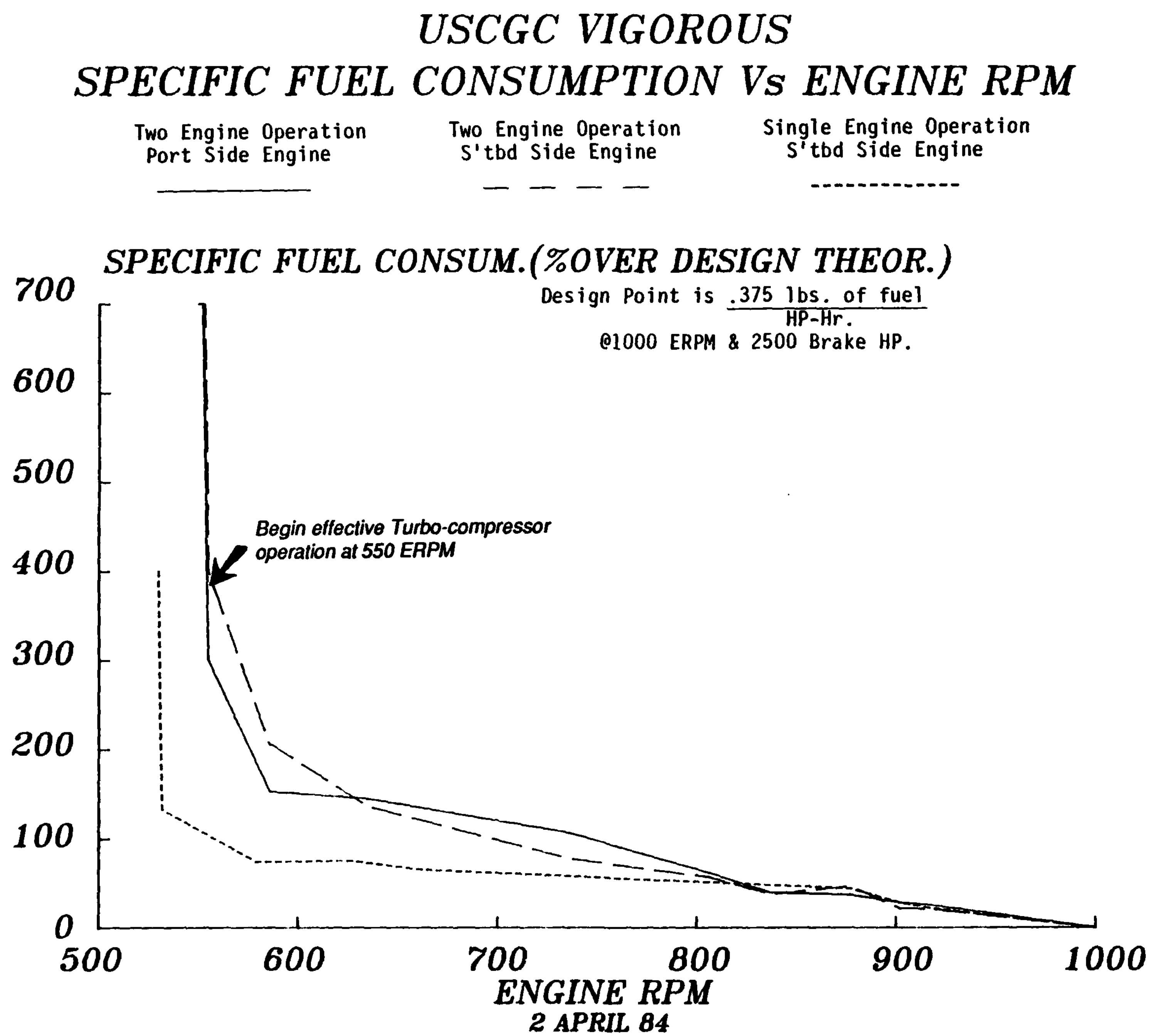


Figure 13. Specific Fuel Consumption vs Engine RPM

compressor and is a good reason for not letting these engines run at or below idle speed of 550 rpm for extended periods of time.

The curves for two engine operation in Figure 13 show the similarity of operation of the engines when sharing the load and running on similar speed-power curves. A fairly significant change occurs when on single engine operation. Single engine specific fuel consumption is much lower compared to duel engine operations when operating below 800 engine rpm.

The data on fuel consumed is used to generate a wealth of useful information including fuel efficiency, vessel endurance, range and specific fuel consumption at specific points on the speed-power curve:

		Units
Let GPH	= Main Engines Fuel Flow (gal/hr) at Speed V	Gal/Hr
h	= Ship Service Generator Fuel Flow (gal/hr) (Constant)	Gal/Hr
GPD	= (GPH + h)24	Gal/Day
V	= Ship Speed (kts)	kts
F.E.	= Main Engine Fuel Efficiency (gal/nm)	Gal/nm
A	= Actual Fuel Capacity of Tanks (gals)	Gals
UF	= Useable Fuel for Operations (gals)	Gals
U.E.	= Utilization Efficiency that is Useable	93%
E	= Vessel Endurance at Speed V (days)	Days
R	= Vessel Range at Speed V (nm)	nm

Then 47,280 = A and A(.93) = UF = 44,000 Gals.

(1) $FE = \frac{GPH}{V}$

(2) $E_V = \frac{44{,}000}{GPD} = \frac{44{,}000}{(GPH+h)24}$

(3) $R_V = 24 \cdot E_V \cdot V$

Speed, efficiency, endurance and range are all a function of fuel flow. They are presented for one and two engines in Table 4 and graphically in Figures 14, 15 and 16.

---

*NOTE: For single engine operation, ship speed must be maintained at 6 knots minimum with the freewheeling shaft set at 5.0 ft pitch in order to maintain sufficient rpm to maintain adequate oil pressure for the reduction gear bearings and servo oil pressure for pitch control. Single engine operation at 12 knot ship speed allows the freewheeling shaft pitch to be set at 9.0 ft for minimum drag while shaft rpm is 150 and lubrication is at its normal level of operation at that point.

TABLE 4

USCGC VIGOROUS FUEL CONSUMPTION DATA

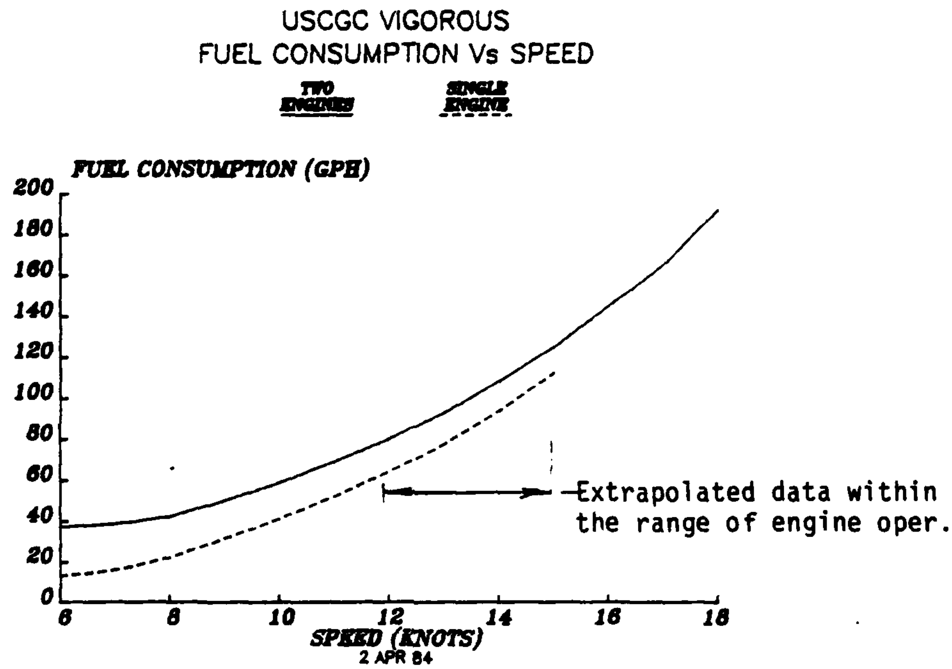
V (kts)	(Gal/Hr) Engines 1	2	FE (Gal/NMI) 1	2	R (NMI) 1	2	E (Days) 1	2
6	13	37	2.0	6.1	10057	6362	105	44
7	16	38.5	2.2	5.5	15024	7163	89	43
8	22	42	2.8	5.2	13283	7570	69	39
10	41	58	4.1	5.8	9670	6984	40	29
12	65	80	5.7	6.6	7707	6250	27	22
14	(94)	109	(7.3)	8.9	(6253)	5450	(19)	16
16	--	145	--	7.8	--	4708	--	12
18	--	192	--	10.6	--	4030	--	9

( ) represents extrapolated data within range of engine operation capability.

Useable Fuel Capacity = 44,000 Gals

UF = .93
h = 4.5 Gal/hr.

210' WMEC 627
FUEL CONSUMPTION & EFFICIENCY



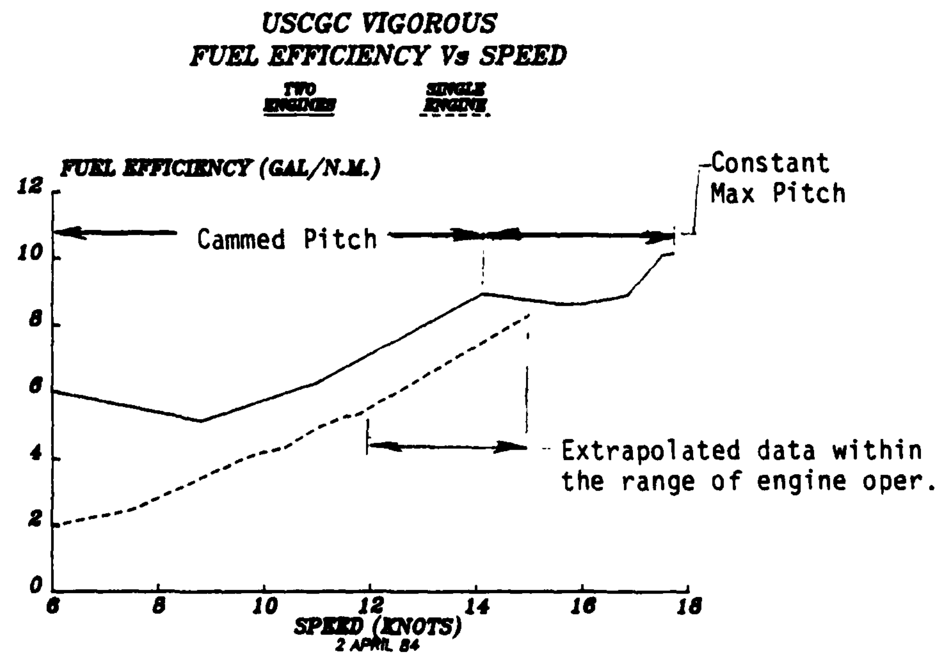


FIGURE 14. FUEL CONSUMPTION & EFFICIENCY vs SPEED

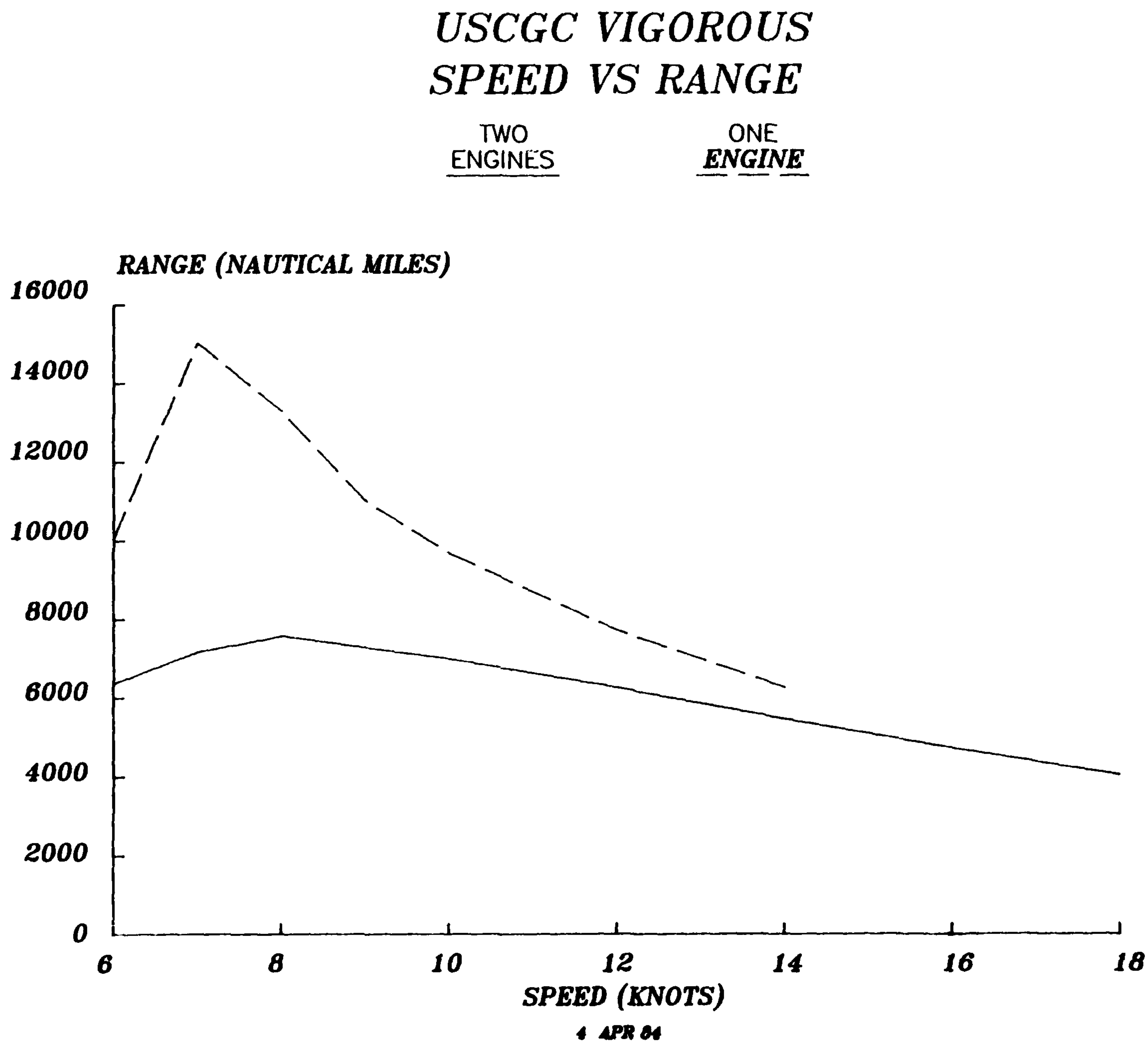


Figure 15. Speed vs Range

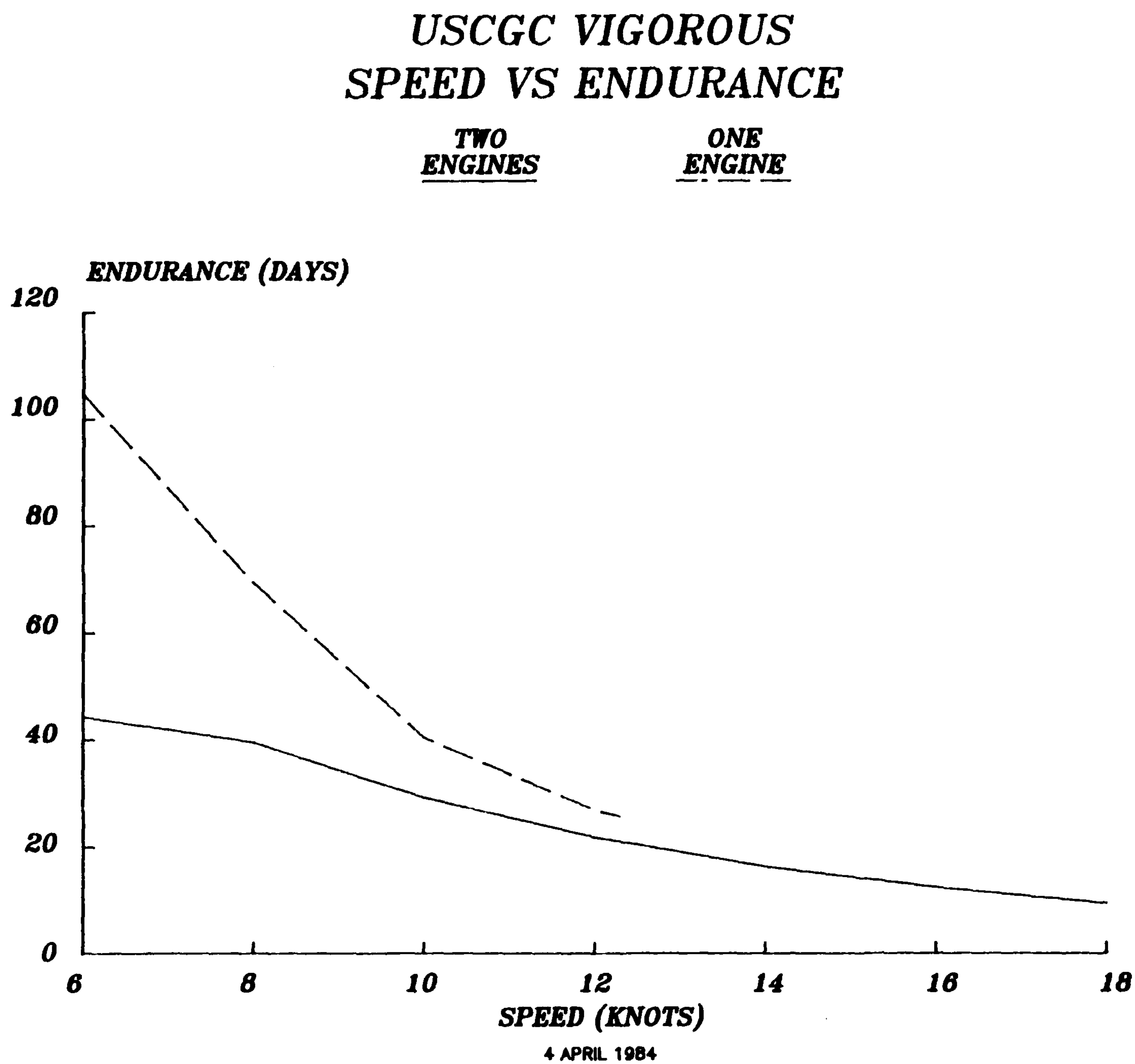


Figure 16. Speed vs Endurance

Noise Levels - Sound levels were taken with the use of a Bruel & Kjaer type 213H hand-held meter throughout the ship as shown in Table 5. Noise levels in all living spaces and the engine room control booth aboard the VIGOROUS are well within ISO safety standards.

Those measurements above 85 dBA in the engine room were plotted on the ISO standard curve (Figure 17). This data indicates that the maximum duration of human exposure is less than three hours for engine room locations on Decks 2 and 3. Engine room watchstanders working outside the control booth should wear ear protection equipment. Other measurements made on board at various locations (see Table 5) were less than 85 dBA and thus below the 16 hour exposure limit, so they were not plotted on the ISO curve.

Structureborne Vibrations - Vibration levels were measured in the VIGOROUS engine room, as shown in Appendix A, Figure A-3. This measurement was made in response to ship's concern about possible vibration problems with the starboard drive train. No abnormal problems were encountered when monitoring the system over full range of speed-power. Frequency analysis of the data showed as many as eight low energy harmonics of the fundamental vibration mode (approximately 60-100 Hz) over the full engine range. These harmonics attributed to bull gear and pinion meshing. Figure 18 depicts a typical vibration spectra for Accelerometer No. 6 (location shown on Figure A-3) with various traces superimposed to show the progression of nodes as speed increased from 170-240 shaft rpm (560-790 rpm).

No problems were experienced with the propulsion shafts during the four day test. The horsepower instrumentation was left installed on the VIGOROUS during its one month patrol; horsepower and rpm were monitored during this time and performed well the entire trip.

SUMMARY

The 210' medium endurance cutter has good seakeeping capabilities in a four foot multidirectional sea state. The CGC ACTIVE was able to transit for twelve hours in nine foot seas without slamming or pitching excessively. The 210' class has good rudder control, however high speed (12 knots or greater) turns cause excessive heel with more than 10 degrees rudder.

The final fuel consumption data shows that single engine operation is very advantageous to extending the range of the vessel up to 12 knots operation with the maximum range 15,000 miles achieved at 7 knot operation. That is approximately twice the range achieved with two engine operation at 7 knots.

Fuel efficiency is defined as gallons consumed per nautical mile traveled. Single engine operation for the CGC VIGOROUS was always more efficient than duel engine operation. High speed two engine operation is most fuel efficient at 16 knots. The 210' cutter is a very fuel efficient platform.

Noise levels in all living spaces and the engineroom control booth were well within ISO safety standards. There were no abnormal structure/machinery vibrations recorded aboard the VIGOROUS.

TABLE 5

USCGC VIGOROUS - SOUND SURVEY
2 April 1984

LOCATION	SINGLE ENGINE (stbd) OPERATION								DUEL ENGINE OPERATION							
	5 knots 160 srpm		8.8 knots 190 srpm		10 knots 220 srpm		12 knots 250 srpm		3 knots 150 srpm		11 knots 190 srpm		15 knots 240 srpm		18 knots 270 srpm	
	dBA	dBC	dBA	dBC	dBA	dBC	dBA	dBC	dBA	dBC	dBA	dBC	dBA	dBC	dBA	dBC
Bridge	50	72	50	74	50	74	50	--	55	73	54	77	54	78	55	79
Fwd. Berthing	59	73	63	74	64	74	64	74	57	72	55	72	56	74	56	76
Berthing	60	72	59	76	61	76	61	76	54	74	55	74	56	73	57	74
Ward Room	59	75	59	75	60	75	60	76	59	78	67	81	63	79	--	--
Chief's Mess	64	76	67	--	69	81	70	82	65	81	67	80	69	82	70	83
Ship's Office	67	82	68	83	68	84	67	84	69	84	69	83	85	85	--	--
Mess Deck	--	--	73	85	--	--	--	--	71	84	75	88	76	86	77	89
Log Office	68	88	71	82	71	82	70	84	73	84	69	82	74	87	74	89
Control Booth	68	79	69	83	72	84	72	85	71	84	72	84	77	85	77	90
Eng. Rm. Deck 2	88	101	99	103	99	102	104	104	99	101	102	105	105	102	105	108
Eng. Rm. Deck 3	97	103	101	103	102	105	106	107	101	105	103	106	108	110	111	112
Aft Steering	78	86	80	87	78	88	80	91	82	89	80	88	84	95	84	104
Fan Tail	78	94	76	95	76	96	76	96	77	95	79	99	78	99	78	98

-- No reading taken
Waves 1 ft.
Wind light and variable

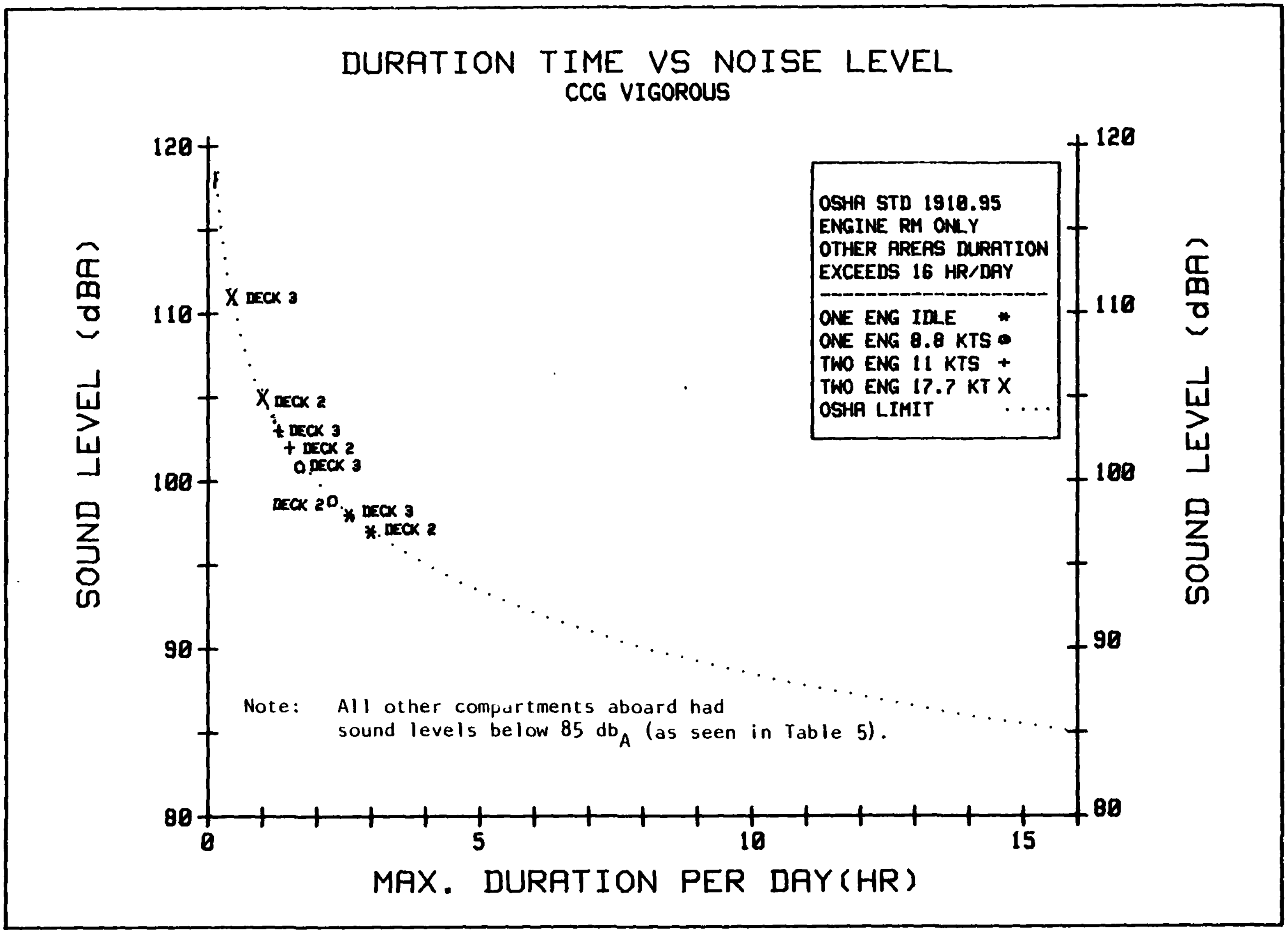


Figure 17. Sound Levels

USCG VIGOROUS

Vibration Analysis on Gear Reduction Case

Bruel & Kjaer Type 4384 Accel., Ser. No. 1060892
(Vertical Mounting - St'bd Side Inboard)
Accelerometer #6 on page A-2

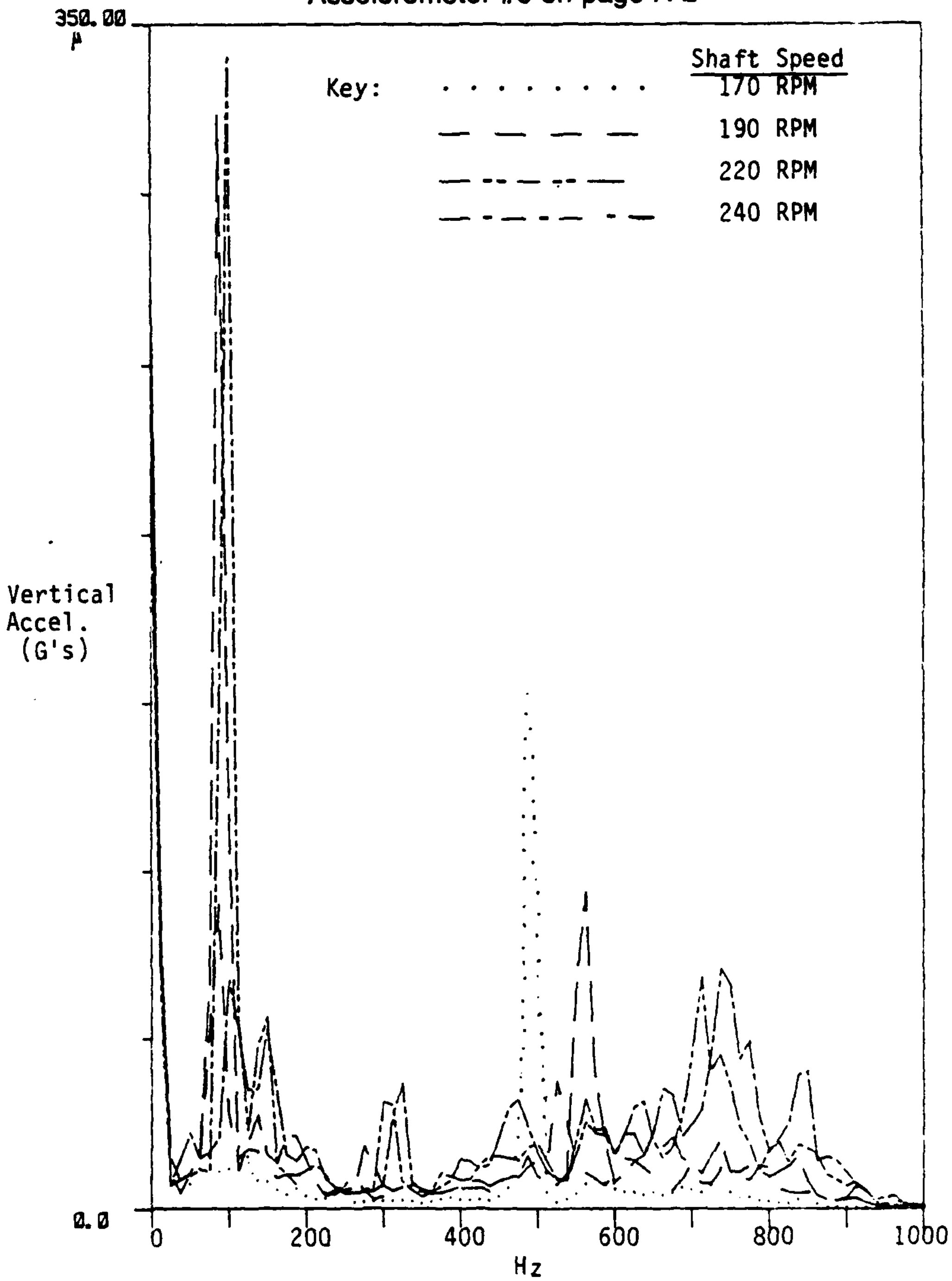


FIGURE 18. VIBRATION ANALYSIS ON GEAR REDUCTION CASE

REFERENCES

1. General Test Plan for Marine Vehicle Testing by LCDR M.J. GOODWIN, USCG, June 1981.

2. BHATTACHARYYA, R., "Dynamics of Marine Vehicles", John Wiley & Sons, New York 1978.

APPENDIX A
EQUIPMENT DESCRIPTION

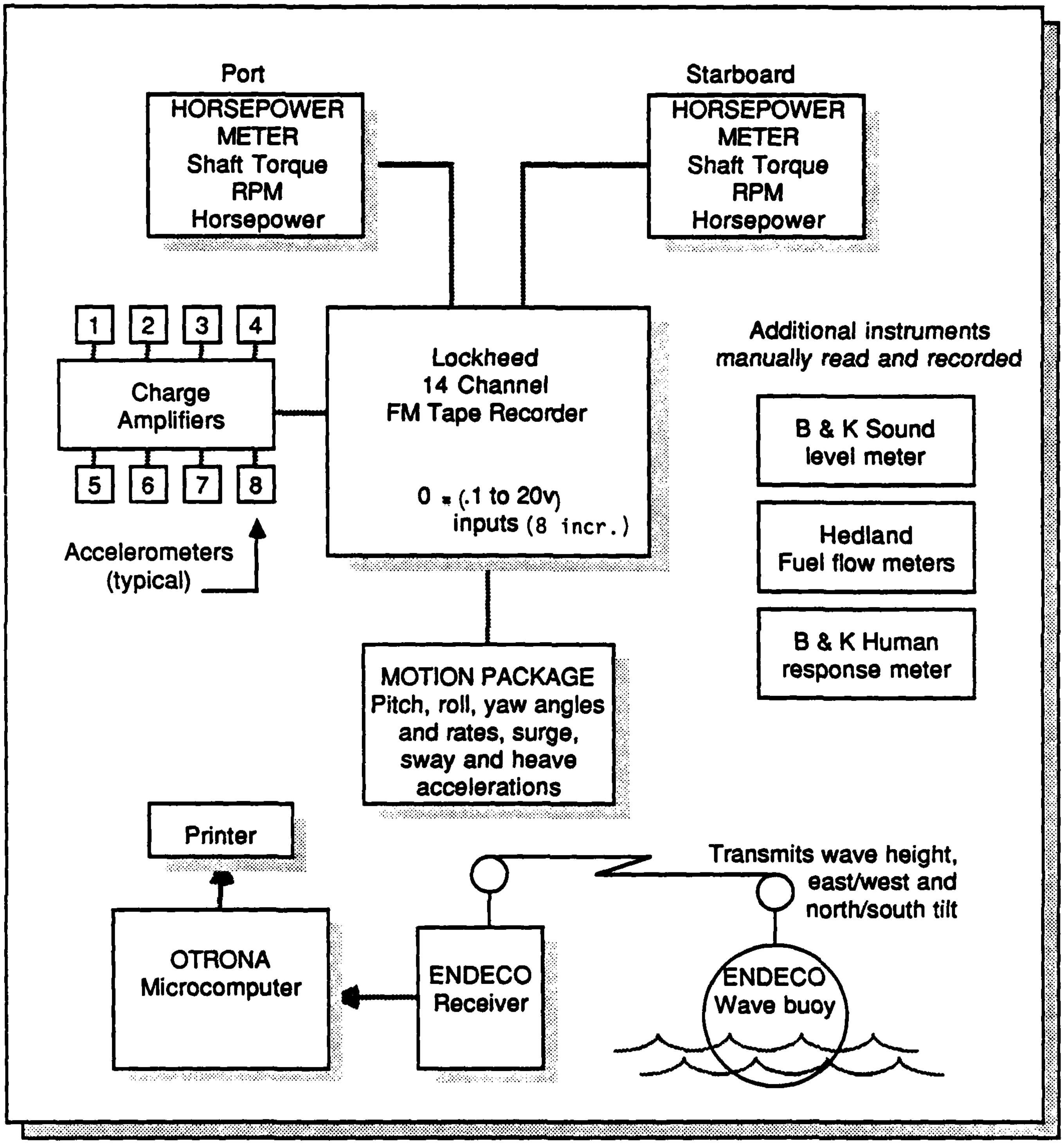


Figure A-1. Block Diagram of Data Acquisition System

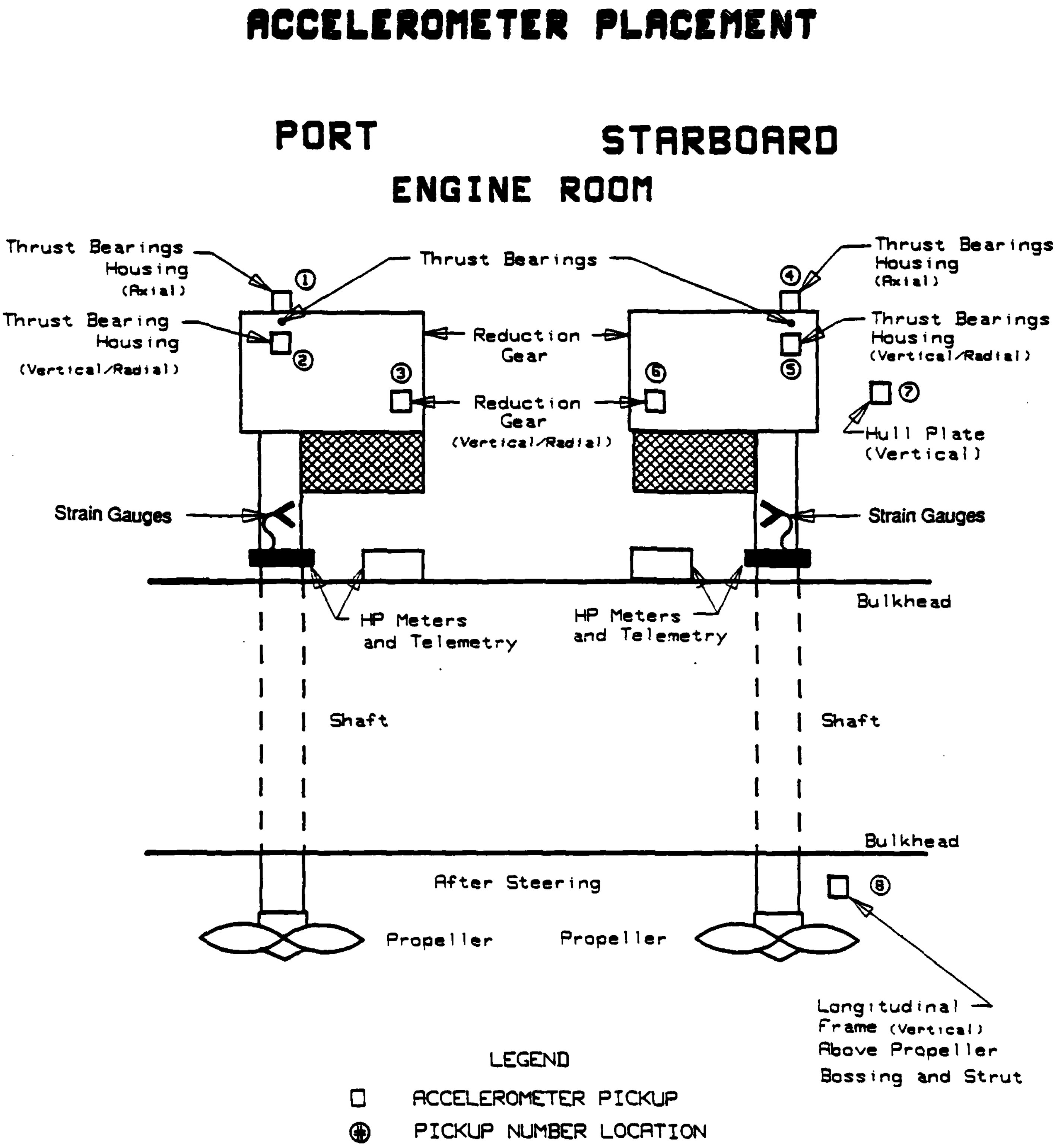


Figure A-2. Engine Room Accelerometer Placement

TABLE A-3

TABLE OF ACCELEROMETER CHARACTERISTICS

BRUEL & KJAER TYPE	SERIAL NO.	CHARGE SENSITIVITY (pC/g)
4368	1108856	53.3
"	1108857	50.7
"	1108858	50.9
"	1108859	54.0
4384	999340	9.84
"	1042978	98.6
"	1060892	9.88
"	1051631	9.92
"	1051741	9.98
"	1012012	96.5

TABLE A-4

DESCRIPTION OF INSTRUMENTATION

EQUIPMENT	DESCRIPTION
SHIP MOTION PACKAGES (2) HUMPHREY, Inc.	This unit consists of a vertical gyro, a vertically stabilized three-axis accelerometer assembly, a directional gyroscope, a three-axis rate gyro assembly and all necessary power supplies and power switching relays. Nine outputs are available at ± 1 or ± 5 volts full scale with or without a 10 Hz low pass filter. Full-scale outputs can be varied as the table below indicates.
Pitch Angles	± 45°, 25° or 10°
Roll Angles	± 45°, 25° or 10°
Yaw Angles	± 175°
Pitch and Roll Rate	60, 30 or 10 deg/sec
Yaw Rate	30, 10 or 5 deg/sec
Surge & Sway Acceleration	± 1.0 or 0.5 G's
Heave Acceleration	± 2.0 or 0.5 G's
STORE 14D ANALOG TAPE RECORDER Lockheed Electronics Company (2)	This analog tape recorder can record up to 14 channels including one voice channel which records on channel 14 and overruns data if recorded on that channel. It has seven variable speeds from 15/16 IPS up to 60 IPS. It can attenuate signals from 0.1 to 20 volts peak to peak normalizing the recorded signal to 1 volt peak to peak output.
ENDECO 956 WAVE TRACK BUOY	This orbital following wave buoy measures wave height and direction. It transmits three digital signals; wave height, buoy tilt (East-West), and buoy tilt (North-South) to a remote receiver usually deployed with the test vessel. The digital signals are recorded and analyzed using an Otrona 8:16 microcomputer. The data can be analyzed using either a "LONGUEST-HIGGONS" or "DIGITAL BAND PASS FILTERING" method. The output is Significant Wave Height (H 1/3) and significant period as well as a plot of wave energy vs. frequency and direction. This allows for a determination of the major swell direction and quantification of the extent of a undirectional or confused sea state. Directional accuracy is ± 10°. It can be moored with an accumulator mooring system for long-term monitoring situations.

HUMAN-RESPONSE VIBRATION METER
Type 2512 Bruel & Kjaer (B&K)
Marion, MA

Measures vibration from a tri-axial accelerometer for the evaluation of vibration on the human body in agreement with current ISO standards for Hand-Arm and Whole-Body (including motion sickness) measurement. The complex relationship between level, frequency and time is automatically taken into account in the compututation of equivalent continuous vibration level and exposure dose. Outputs are printed on thermal paper with the use of a Alphanumeric Printer type 2312. Outputs are automatically printed at preselected intervals in the form of: Current Time, Elapsed Time, Peak Acceleration (dB), Equivalent Exposure (dB) and Percent of a particular ISO standard selected which has been reached at that elapsed time.

TRIAXIAL SEAT ACCELEROMETER
Type 4322
(used with B&K Meter Type 2512)

This accelerometer is especially designed for detecting vibration motion in connection with the measurement of whole-body vibration and can be put under the buttocks of a seated person.

Frequency Range:	0.1 Hz to 2 kHz (± 5%)
Charge Sensitivity:	1 pC/ms^{-2} ± 2% 10 pC/g
Piezoelectric Material:	PZ27
	Delta Shear Configuration

ACCELEROMETER CHARGE AMPLIFIERS Type 2635 and 2651 Bruel & Kjaer
Marion, MA

Various ship vibration measurements are made using Bruel & Kjaer (B&K) accelerometers and charge amplifiers. The output of the charge amplifiers are recorded on magnetic tape. Two types of B&K accelerometers are used; they are the 4368 and the 4384. Two types of charge amplifiers are used; they are the Model 2635 and the Model 2651. The 2365 is a battery operated (stand alone) charge amplifier with transducers sensitivity conditioning from 0.1 to 10.99 pC/ms^{-2}.

Frequency Range:	
Acceleration	.2Hz to 100kHz
Velocity	1Hz to 10kHz
Displacement	1Hz to 1kHz

The Model 2651 charge amplifier needs a power supply (and is packaged in a pack of four amplifiers with the power supply); transducer sensitivity conditioning settings of 0.1, 1, and 10 mV/pC.

Frequency Range:
Acceleration .003 to 200kHz

General B&K accelerometer information follows:

Model	Charge Sensitivity	Frequency Range	Temperature Range (deg. C)
4368	4.8 pC/ms^{-2}	.2 to 5000	-74 to 250
4384	1 $\pm$ 2%	.2 to 9200	-74 to 250

FUEL FLOW METERS
HEDLAND
Racine, WI

In-line flow meters are direct reading units requiring no electrical connections or read-out devices. Scales are based on a specific gravity of 0.84 for fuel oil. Accuracy is within $\pm$ 5% of full scale.

HORSEPOWER METER 1202A (2)
ACUREX AUTODATA,
Mountain View, CA

The 1202A measurement system measures shaft torque and rpm and calculates horsepower from that information (HP = Torque x rpm x Constant). The shaft is strain gauged for torque. A transmitter collar and antenna are bolted to the shaft in order to power and transmit FM signals from the strain gauge bridge. Three simultaneous analog outputs are provided at the readout box (Torque, HP and rpm). Calibration using a shunt resister is usually conducted because a known torque load is difficult to apply to a vessel in the water. This method simulates a torque load by shunting a gauge with a known value of resistance.

SPECIFICATIONS

Accuracy:	Torque	$\pm$ 1% of full scale
	rpm	$\mp$ 0.25% of full scale
	Horsepower	$\mp$ 1.5% of full scale

SOUND LEVEL METER TYPE 213H
Bruel and Kjaer
Marlborough, MA

This hand-held sound level meter measures levels from 50 to 130 dB with A or C weighting filters. It can be used with fast or slow response. Calibration is done by using a Sound Level Calibration unit Type 4230. The sound pressure level of the calibrator is 93.6 dB.

APPENDIX B
DATA TABLES

TABLE B-1

WAVE SPECTRA (USCGC ACTIVE SEAKEEPING)
POWER SPECTRAL DENSITY (PSD)

Center Frequency (Hz)	Center Period (S)	Energy Density (FT-SQ/Hz)	Mean Direction (DEG)
.070	14.3	1.31	66.
.080	12.5	1.31	104.
.090	11.1	6.13	91.
.100	10.0	4.64	327.
.110	9.1	12.12	292.
.120	8.3	11.94	288.
.130	7.7	7.85	295.
.140	7.1	8.59	297.
.150	6.7	3.93	324.
.160	6.2	10.14	19.
.170	5.9	3.04	33.
.180	5.6	4.19	36.
.190	5.3	3.19	39.
.200	5.0	2.87	41.
.210	4.8	1.53	41.
.220	4.5	5.99	38.
.230	4.3	3.71	35.
.240	4.2	1.59	26.
.250	4.0	3.39	20.
.260	3.8	1.50	22.
.270	3.7	3.47	22.
.280	3.6	2.38	16.
.290	3.4	2.46	7.
.300	3.3	1.39	1.

SIGNIFICANT WAVE HEIGHT (H 1/3) = 4.2
ROOT-MEAN-SQUARE WAVE HEIGHT = 3.0
AVERAGE PERIOD = 6.17

TABLE B-2

USCGC VIGOROUS - SPIRAL TESTS

RUDDER ANGLE (deg)	YAW RATE (deg/sec) 6 knots	12 knots
20R	1.24	
15	1.12	
10	0.89	1.36
5	0.59	0.82
3	0.32	0.58
1	0.14	0.22
0	0.00	0.00
1L	-0.12	-0.15
3	-0.27	-0.33
5	-0.47	-0.68
10	-0.74	-1.42
15	-0.91	
20	-1.13	
15	-0.90	
10	-0.70	
5	-0.40	-0.87
3	-0.29	-0.46
1	-0.19	-0.09
0	-0.03	-0.01
1R	+0.11	+0.16
3	0.28	0.42
5	0.41	0.68
10	0.86	1.22
15	1.11	
20	1.30	

Data not collected above 10 degrees rudder during 12 knot run at the request of Commanding Officer to limit vessel heel.

TABLE B-3

USCGC VIGOROUS - ZIG-ZAG MANEUVER

	SPEED	
	4 knots	10 knots
OVERSHOOT #1 (deg)	6.6	10.4
OVERSHOOT #2 (deg)	6.4	10.4
OVERSHOOT #3 (deg)	6.6	11.5
OVERSHOOT #4 (deg)	6.4	10.4
Time to Second Execute (sec)	45	32
Period (sec)	192	88

TABLE B-4

USCGC VIGOROUS - SPEED VS HORSEPOWER
One Engine STBD with Port Shaft Free Wheeling
2 April 1984

SPEED (knots)	SHAFT HP	SHAFT RPM	PROPELLER PITCH (ft)
0	40	160	0.2
2.7	60	160	1.8
4.9	115	160	4.0
7.5	230	175	6.0
8.8	380	189	7.0
9.6	485	200	7.2
10.0	550	209	7.1
10.4	630	220	7.0
11.0	765	230	7.2
11.5	905	238	7.2
11.8	1020	248	7.2

Note: At 6 knots, 5 feet of pitch must be maintained on the freewheeling shaft for the proper rpm level to drive the lubrication pump.

At 12 knots, 9 feet pitch maintains 150 srpm on the freewheeling shaft, enough pitch for the lubrication pump with reduced drag.

TABLE B-5

USCGC VIGOROUS - SPEED VS HORSEPOWER
Two Engine Operations
2 April 1984

SPEED (knots)	SHAFT HP PORT	SHAFT HP STBD	SHAFT HP TOTAL	SHAFT RPM	PROPELLER PITCH (ft)
0	50	50	100	168	0
3.2	60	50	110	167	1.8
6.0	100	80	180	167	4.0
8.8	185	175	360	170	6.1
11.0	300	340	640	192	7.3
14.1	680	790	1470	223	8.6
15.5	950	980	1930	243	8.6
16.0	1150	1150	2300	253	8.6
16.8	1270	1300	2570	265	8.6
17.5	1430	1518	2948	273	8.6
17.7	1650	1630	3280	278	8.6

NOTE: Full power was not utilized because one engine had piston rings replaced 35 engine hours earlier.