LEVEL II

CG-D-26-80

(12)

COAST GUARD CUTTER DUTY CYCLE AND PROPELLER/DIESEL ENGINE EFFICIENCY STUDY

DTIC
ELECTE
JUL 20 1981
E

REPRINT
MAY 1981

U.S. DEPARTMENT OF TRANSPORTATION

RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
TRANSPORTATION SYSTEMS CENTER ● CAMBRIDGE MA 02142

PREPARED FOR UNITED STATES COAST GUARD
OFFICE OF RESEARCH AND DEVELOPMENT ● WASHINGTON DC 20593

18) / -D.TSC

Technical Report Documentation Page

1. Report No. CG-D-26-80 USCG-80-8	2. Government Accession No. AD-A201 567	3. Recipient's Catalog No.
4. Title and Subtitle COAST GUARD CUTTER DUTY CYCLE AND PROPELLER/DIESEL ENGINE EFFICIENCY STUDY		5. Report Date Reprint 11 May 1981
		6. Performing Organization Code
7. Author(s) Q.A. Baker, J. O. Storment		8. Performing Organization Report No. DOT-TSC-USCG-80-8 11-4132-003/004
9. Performing Organization Name and Address Southwest Research Institute* 622 Culebra Road San Antonio TX 78284		10. Work Unit No. (TRAIS) CG007/R1014
		11. Contract or Grant No. DOT-TSC-920
12. Sponsoring Agency Name and Address U.S. Department of Transportation U.S. Coast Guard Office of Research and Development Washington DC 20593		13. Type of Report and Period Covered Final Report Sep. 1975 — Aug. 1980
		14. Sponsoring Agency Code G-DMT-3

16. Abstract

This report covers an investigation into methods to reduce the fuel consumption of the large main propulsion diesel engines used on 378 high-endurance and 210B medium-endurance Coast Guard cutters. This investigation involved, first, defining the duty cycles for the cutters and, second, analyzing the efficiency of the controllable pitch propellers and main diesel engines. Based on this information, cycle composite cutter fuel consumption figures were calculated and changes in the operational procedures of these cutters were recommended where fuel savings appeared to be possible. Methods of reducing fuel consumption which were analyzed were changes in the propeller pitch/engine speed combination needed to produce a given cutter speed, and possible single-engine operation at low cutter speeds.

A study of the duty cycle of an icebreaker is also included in the program.

17. Key Words High Endurance Coast Guard Cutters, Medium-Endurance Coast Guard Cutters, Coast Guard Icebreakers, Fuel Consumption, Controllable Pitch Propellers, Duty Cycles, Diesel Engines	18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 88	22. Price

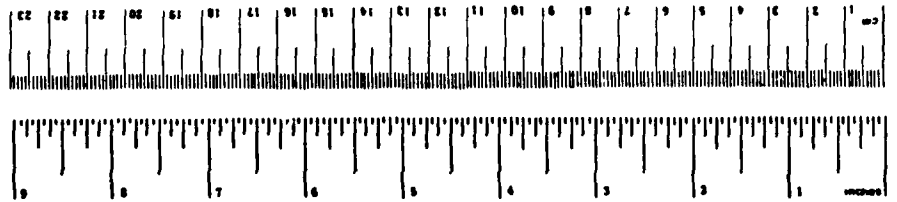Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

PREFACE

Accession For

NTIS	GRA&I	X
DTIC TAB		☐
Unannounced		☐
Justification		

By
Distribution/
Availability Codes
Avail and/or
Dist | Special

A

iii

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		
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.8	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	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
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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		
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	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	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	35	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

1.1 BACKGROUND

An investigation of methods to reduce fuel consumption and improve emissions of large in-service diesel engines used in locomotives and several classes of Coast Guard cutters was begun by Southwest Research Institute in November 1974, under Contract DOT-TSC-920. This report encompasses the portion of that program which dealt with the optimization of fuel consumption for several classes of the larger Coast Guard cutters. These classes include the 378-ft. High-Endurance cutters (378 WHEC), the 210-ft. B series Medium-Endurance cutters (210B WMEC), and Icebreakers (WAGB).

The fuel consumption of the main diesel engines of these cutters is of prime importance to the Coast Guard since they use a major portion of the diesel fuel consumed by the entire Coast Guard cutter fleet. A DOT report[1] placed this fuel consumption at 2.9×10^7 gallons, of which approximately 37%, or 1.8×10^7 gallons, was consumed by the diesel engines of the cutter classes of interest. However, this figure represents the fuel consumed by the main and auxiliary diesel power plants carried on board some of these cutters. The exact portion of usage by the main diesels alone is unknown, but a reasonable estimate would be that at least two-thirds of the fuel consumed could be attributed to the main diesel engines. There are slightly over 100 such engines in Coast Guard ships.[2]

Programmed variations in the operational characteristics of the medium- and high-endurance cutters (WMEC's and WHEC's) are possible since they are equipped with variable-pitch propellers directly driven by the main diesel engines through a fixed-ratio speed reduction system. [Icebreakers (WAGB) have fixed-pitch propellers.] This variable pitch feature allows for an infinite number of pitch/engine speed settings which will produce a given ship speed. However, the ships operate only at selected settings which are defined by a programmed pitch schedule. Optimization of the pitch schedule could produce acceptable cutter performance with minimum fuel consumption.

1.2 OBJECTIVES

The objectives of the tasks in this program were:

a. Define duty cycles for the high-endurance (378 WHEC) and medium-endurance (210B WMEC) cutters, and icebreakers (WAGB). That is, define the characteristic distribution of operating time among the various engine speed/pitch modes for each class of ship.

b. Obtain a set of time-based modal weighting factors which define the characteristic utilization for normal operation of the main diesel engines in these cutters.

c. Determine the overall effect of engine mode and propeller pitch changes on fuel consumption and cutter performance through analysis of propeller pitch/efficiency data for medium-endurance and high-endurance cutters.

1.3 APPROACH

Data needed to define the duty cycles for the three classes of Coast Guard cutters covered in this report were obtained by instrumenting one or more cutters of each class and, where possible, through analysis of ships' log books. Further information on cutter operating practices and systems was furnished by ships' personnel and by the Naval Engineering Maintenance Branch of the Coast Guard.

---

[1] Willis, Lt., B., "WHEC 378 Fuel Consumption Study", U.S. Coast Guard Report Prepared by G-OP Energy Branch, March 11, 1980.
[2] Janes Fighting Ships, 1972-1973.

Analysis of propeller pitch/efficiency for the medium-endurance and high-endurance cutters required the use of design data for the controllable pitch propellers and for the cutters themselves. This information was obtained through the Coast Guard and from the technical literature. The performance maps for the main diesel engines were developed in Phase I of this program from information furnished by engine manufacturers, as well as from a search of published technical literature.[3]

The result of the study was an estimate of cutter fuel consumption through a correlation between propeller and engine performance at the various operating modes. These estimates were then weighted according to the duty cycle information (modal weighting factors) to produce cycle composite fuel consumption figures. With knowledge of propeller and engine performance, recommendations were made on operational changes which could reduce fuel consumption.

It should be pointed out that the Icebreakers were not included in the propeller pitch/efficiency study since they employed fixed pitch propellers and, as such, did not have the latitude for variable propeller performance as with the WHEC and WMEC. Consequently, the sole objective in working with the Icebreakers was to define their duty cycle.

[3]Storment, J. O., R. J. Mathis, and C. D. Wood, A Study of Fuel Economy and Emission Reduction Methods for Marine and Locomotive Diesel Engines, Report No. DOT-TSC-OST-75-41 or CG-D-124-75, Department of Transportation/U.S. Coast Guard, September 1975.

2. CONCLUSIONS

2.1 DUTY CYCLE DATA

a. Each ship, in both WHEC and WMEC classes, characteristically operated in a specific set of throttle positions which correspond to conditions of engine speed and load (or propeller pitch), and the percentage time spent in each throttle position was fairly constant from month to month.

b. The percentage time spent in each operating mode and the total accumulated time for the two main propulsion engines were very nearly equal for the WHEC's.

c. The distribution of percentage operating time among the throttle positions for the two engines on the WMEC's varied due to either frequent single-engine operation or the desire to balance power output between the two engines.

d. Because of frequent two-engine operation (one per propeller) and the desire to balance shaft speed for the pair of fixed-pitch propellers, the distribution of percentage operating time varied among the modes for the engines on the icebreaker WESTWIND, the only WAGB included in this study.

2.2 FUEL CONSUMPTION ANALYSIS FOR MEDIUM- AND HIGH-ENDURANCE CUTTERS

a. Fuel consumption decreased for both classes of ships as propeller pitch ratio was increased for a constant ship speed throughout the operating range when operating normally with both propellers driven.

b. The most substantial projected fuel savings resulted from a decrease in propeller pitch at constant engine speed, decreasing shaft horsepower and cutter speed for both WMEC and WHEC.

c. No significant reduction in fuel consumption appeared possible for the WMEC when operating normally by increasing pitch ratio at constant ship speed since the cutter is currently operating at or near a condition of minimum fuel usage.

d. Of the two propellers utilized on the WHEC's, the Escher-Wyss was found to be significantly more efficient, resulting in a decrease in fuel consumption of approximately 14% on a cycle composite basis over the Propulsion Systems, Inc. (PSI) design when operating on the current pitch schedule.

e. Fuel consumption savings are theoretically possible in the 2/3 and Full operating modes on the WHEC without sacrificing cutter speed if the pitch can be increased beyond the present limit of 1.0 to 1.4. The limitation here is the engine torque available to turn the prop at higher pitch settings.

f. Single-engine operation of the WHEC did not reduce fuel consumption at ship speeds of 10 knots or more. Single-engine operation is believed to be most beneficial below this speed; however, propeller and cutter performance data were not available to allow a firm conclusion on this point.

g. When operating with a single propeller, the free propeller should be rotating at the maximum pitch setting. A locked propeller results in a large increase in drag and, therefore, higher fuel consumption.

3. RECOMMENDATIONS

a. Obtain engine and cutter performance data for the WMEC's and WHEC's through cutter testing. The data should be extensive enough to reconstruct the propeller diagrams. Provisions should be made to measure engine fuel consumption, power output (possibly using a torsion meter), engine speed, propeller pitch, and ship speed for points throughout the operating range. As part of these tests, determine the maximum pitch which can be obtained throughout the diesel engine speed range and the resulting cutter speeds.

b. Compare the performance data to the present propeller diagrams to verify their accuracy. If necessary, correct the propeller diagrams to reflect true cutter operating characteristics. Ascertain that postulated mode changes are possible in practice and that they conserve fuel.

c. Expand the slow ship speed (less than 10 knots) portion of the WHEC propeller diagrams for single-engine and normal two-engine operation, calculate fuel rates for slow-speed operation, and determine if and when single-engine operation has merit. Verify the single-engine operation propeller diagrams through WHEC testing.

d. Perform an analysis of single-engine operation for medium-endurance cutters. Again, this type of operation is most advantageous in the ship speed range below 10 knots, and the analysis should concentrate on this region. This would require generation of a single-engine operation propeller diagram for this cutter class.

e. The Coast Guard should perform an in-house cost/benefit analysis to determine the advantages of replacing the WHEC Propulsion Systems, Inc. (PSI) propellers with the more efficient Escher-Wyss design. Because of the accuracy of the data on hand, performance data as obtained in recommendation 1 for both propeller designs should be the basis for the analysis.

4. DUTY CYCLE DATA ACQUISITION

4.1 PROPULSION SYSTEMS AND OPERATING MODES

4.1.1 High- and Medium-Endurance Cutters (WHEC's and WMEC's)

The propulsion systems on the high- and medium-endurance cutters employ a direct-drive concept in which the main propulsion units are coupled directly to variable pitch propellers through a constant-ratio gear reduction system. The main machinery on the WHEC's is a combined diesel engine/gas turbine (CODOG) arrangement in which operation is possible on either gas turbines or diesel engines. The first five WMEC's (210A class) were built with a combined diesel engine/gas turbine (CODAG) arrangement where gas turbines and/or diesel engines could be used. The remainder of the WMEC fleet (210B class) employed only diesel engines for propulsion, again utilizing the direct drive system.[4,5,6]

The diesel engines in both cutter classes operate only in a distinct set of modes which are defined by engine speed and propeller pitch. Mode selection from the pre-programmed pitch schedule is accomplished by the position of a control handle, one for each engine. The arrangement is such that, as the handle is moved from the lowest to the highest setting, propeller pitch is increased from zero to maximum at a constant engine idle speed, at which point speed is increased until it reaches its maximum value while pitch is held at the maximum value. Typical throttle schedules for these engines are plotted in Figures 4-1 and 4-2.

The schedule for the WHEC cutters also includes operating modes (Idle, 1/3, 2/3, Standard, Full, and Flank) which are the designated operating conditions of these ships and are associated with specific handle positions; typical values are shown in the table below. Normally, each ship defines its own schedule. Handle positions above 8 are nonfunctional for diesel engine operation; setting the handles in these positions results in handle position 8 operation. It should be noted that the WHEC is equipped with a continuous throttle control and, therefore, can be operated at conditions that lie between those shown in the table, although this is not done in normal practice.

TABLE 4-1.   TYPICAL HIGH-ENDURANCE CUTTER OPERATING MODES

MODE	HANDLE POSITION	PROPELLER PITCH RATIO	ENGINE RPM
Idle	0	0	450
1/3	3	0.55	450
2/3	5.5	1.0	450
Standard	7	1.0	750
Full	8	1.0	900
Flank	8-10	1.0	900

---

[4] Wennberg, P. K., "The Design of the Main Propulsion Machinery Plant Installed in the USCG HAMILTON (WPG-715)", Society of Naval Architects and Marine Engineers Transactions, Vol. 74, 1966.

[5] Russel, H. E., "First Coast Guard High-Endurance Cutter in Twenty Years", Naval Engineers Journal, October 1965.

[6] Anonymous, "'Reliance' Class Cutters", Shipbuilding and Shipping Record, November 4, 1965.
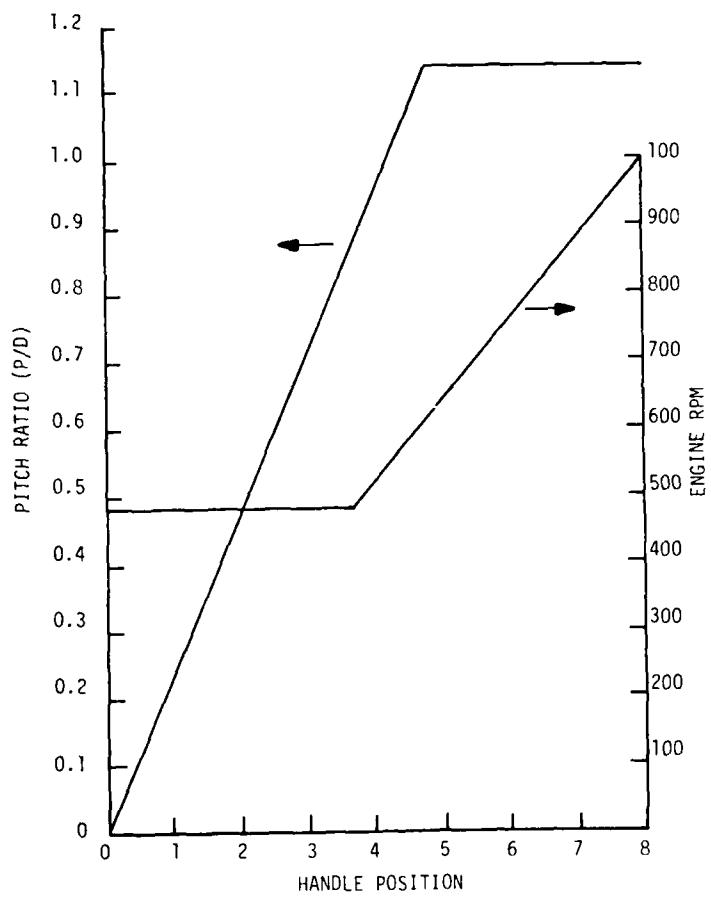
FIGURE 4-1. 210B WMEC THROTTLE SCHEDULE
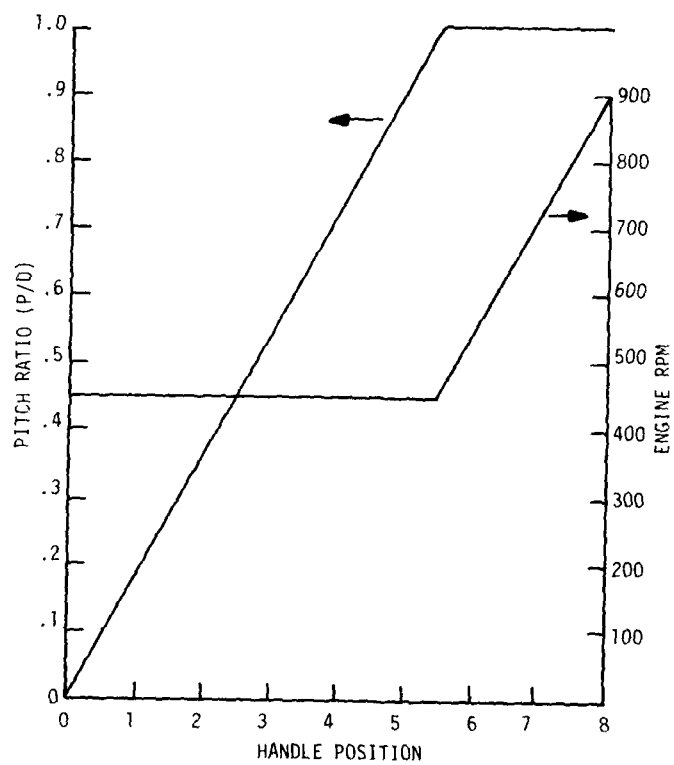
WHEC PITCH SCHEDULE
(USED ON ALL WHEC'S)

FIGURE 4-2.   378-FOOT WHEC THROTTLE SCHEDULE

The main diesel engines of the WMEC and WHEC are equipped with governors that maintain the designated engine speed (or shaft speed) for a particular throttle position as long as the load does not surpass the maximum engine capacity at that speed. Literature sources (4)(6) state that, if the load demand exceeds this maximum figure, the control system automatically reduces propeller pitch until the load demand equals the power available at that engine speed. Consequently, a constant-speed/variable-load system is employed which produces the nominal power output that is required to achieve the desired propeller speed under average cutter operating conditions (wave height, wind velocity, draft, etc.). Changes in these conditions will increase or decrease the engine power output demand relative to this nominal value, and the engine control mechanism will respond accordingly to maintain constant speed. However, information from the Coast Guard[7] contradicts these sources; presently, propeller pitch does not change unless the control handle is moved. The engines are not protected from overload; consequently, engine speed decreases if overload occurs.

4.1.2 WIND Class Icebreakers (WAGB)

The WIND Class Icebreakers employ a diesel-electric drive system in which each of the two constant-pitch propellers is driven by a motor which, in turn, is powered by a pair of engine/generator sets. With this system, propeller shaft speed is independent of engine speed, but is controlled by generator load as shown in Table 4-2.

TABLE 4-2. PARAMETER VALUES FOR ICEBREAKER OPERATING WAGB WESTWIND

Mode	Shaft RPM	Engine RPM	Gen. Volt.	Gen. Amp	Gen. HP
1/3	38	395	310	100- 150	42- 63
2/3	8C	430	650-675	300- 500	263- 456
Standard	105	460	850-900	600- 700	688- 850
Full	125-130	460	900-950	1200-1400	1458-1798
Flank	125-130	460	900-950	1800-2000	2187-2565

4.2 DUTY CYCLE RECORDING EQUIPMENT

The time of operation in each handle position for these cutters was acquired by two methods; first, engine room logs which contained a record of all bell order (operating mode) changes made by engine room personnel were analyzed to extract any duty cycle data they might contain. However, this approach was applicable only to the WHEC class since the other two classes did not keep such a log. The second method, in which the ships were instrumented with recorders to log total operating time and time spent in each throttle position for each engine, was employed for all three classes.

The duty cycle recorder system instrumentation utilized signals from the engine/ propeller control system to record throttle position and operating time. However, due to differences in the control systems of the three types of cutters, the design of the interface joining the control system to the recorders varied among the classes as outlined below.

4.2.1 Medium-Endurance Cutter Instrumentation

The WMEC control system is pneumatic in its operation. Speed and pitch adjustments are accomplished through pressure transmitters which are positioned by cams. For a given handle position, these cams program a particular shaft speed and propeller pitch through air signals to the engine governor and pitch positioner.[6]

---

[7]Telephone conversation with LCDR. D. Reichl, U.S. Coast Guard, June 1980.

The duty cycle recorder system used on these cutters employed a mechanical switching device which was fabricated to fit the engine control camshafts located under the pilot house control console. The switch program was arranged such that the numbered (0 through 8) handle positions activated the recorder channel with the same number, while the "one-half" or in-between positions activated both adjacent channels. A strip chart recorder capable of recording 20 channels of "on/off" events on heat sensitive paper was mounted in the Combat Information Center (CIC) room directly below the control console. Also, two digital run-time meters were installed in the engine room control station to log total individual engine running time.

The interface was connected to the pilot house (bridge) controls. These controls did not function when ship control was transferred to the engine room; as a result, the recording system failed to log this time. The total operating time from the run time meters was compared to the sum of the individual modal times from the strip charts to determine the amount of time actually spent under engine room control.

Additionally, total operating time was needed for the calculations of idling time since the pilot house throttles were left in the "idle" position when (a) engines were indeed idling, (b) engines were under engine room control, (c) engines were secured. Consequently, the charts indicated a large amount of time for the idle position which did not actually involve engine idle operation. The method used to calculate idle time was as follows:

(engine room meter running time) minus (sum of chart recorder times for "non-idle" conditions) minus (estimate of time spent under engine room control) equals (engine idling time).

Duty cycle data was collected from recorders installed on the medium-endurance cutters DECISIVE, VALIANT, and DURABLE (WMEC's 629, 621, and 628).

4.2.2 High-Endurance Cutter Instrumentation

Propeller pitch and engine speed of the WHEC's are regulated by an electronic control system which operates in the same fashion as the pneumatic system described for the WMEC's. Monitoring handle position directly as an indicator of operating mode was impractical in this case. Rather, engine speed was recorded using the voltage output of the shaft tachometer to activate the corresponding channel of a strip chart recorder (one channel per engine) through a voltage comparator. As with the WMEC's, run-time meters logged total individual engine operating time. Idling time was calculated as the difference between total operating time shown on the run-time meters and the sum of "non-idle" operating conditions recorded on the strip chart. Two WHEC's, the HAMILTON and CHASE (nos. 715 and 718), were instrumented in this manner. Additionally, duty cycle data was extracted from the engine room logs of the cutters CHASE and GALLATIN (WHEC 721).

4.2.3 Icebreaker Instrumentation

As previously mentioned, the WIND Class Icebreakers employ a diesel-electric drive system as opposed to a diesel/gas turbine arrangement. Since propeller speed is independent of engine speed for this system, it was necessary to record the generator output as well as the engine speed to determine an operating mode. Consequently, four strip chart recorders, one for each engine/generator set, monitored engine speed and generator voltage and amperage. As with the WHEC's, the voltage output of the tachometers was used to determine engine speed. In this case, the strip chart recorders ran continuously so that total operating time and idle time could be extracted directly from the charts. This system was installed on the WESTWIND (WAGB 281).

4.3 DATA REDUCTION

Reduction of the duty cycle data taken from the high- and medium-endurance cutters amounted to summing, for each channel, the time that information was recorded by that channel. Total time indicated by a channel corresponded to total operating time in a particular mode. Using the information from the run-time meters installed on each engine, idling time was computed as indicated earlier.

Information from the icebreaker's recording system was analyzed in a similar fashion; however, a correlation was necessary between engine speed and generator amperage and voltage to establish an operating mode. Some of the data from the charts fell between two modes, and it was necessary to establish tolerance bands around the recorded parameters. Thus, the grouping of data was determined by a "go-no go" decision as to whether the operating mode was, for example, Standard or Full. A discussion of these variations and their grouping is included in a later section of this report.

Time-based modal factors were computed for each of the cutters indicating the percentage time spent in each operating mode. This was performed on a chart-to-chart basis (approximately one month running time per chart), as well as on a cumulative basis to provide an assessment of month-to-month changes for each cutter.

5. PROPELLER PITCH/EFFICIENCY ANALYSIS

Information was obtained on propeller, cutter, and engine performance of the medium- and high-endurance cutters for the purpose of evaluating the effect of mode changes on fuel consumption and cutter performance. This included propeller diagrams, which relate shaft horsepower to propeller shaft speed throughout the design pitch and speed range, and engine performance maps for the main propulsion units. Since direct-drive propulsion systems were employed, each point on the propeller diagram uniquely determined the engine load and speed conditions. Fuel consumption was computed throughout the range of data available on propeller and engine performance. Also, a cycle composite fuel consumption (the average fuel usage rate based on a pitch schedule and weighted by the time-based modal factors) was developed.

Two discrepancies arose when working with the high-endurance cutters. First, it was found that two different propellers were in use; earlier cutters (WHEC's 715 through 718) were equipped with propellers manufactured by Propulsion Systems, Inc., while the remaining cutters (WHEC 719 - WHEC 726) used an Escher-Wyss design. Consequently, it was necessary to obtain the propeller diagrams for both makes and then perform the analysis for each case. Second, these ships were reported to be approximately 10% over the design weight, which resulted in increased ship draft and increased hull resistance. It was thus necessary to correct propeller diagrams for both configurations to account for the added horsepower necessary to propel the ship at a given speed. The correction was provided by Professors William Vorus and M. G. Parsons of the University of Michigan; a detailed report is included in Appendix A.

Recommendations for changes in the pitch program of the WMEC's and WHEC's for improved fuel consumption were based on data from the propeller diagrams and engine fuel consumption maps; these data were analyzed by two methods. First, alterations in the engine speed/propeller pitch combinations were restricted to produce the same vessel speed in each mode as the existing schedule; second, changes were made without this restriction.

Additionally, single-engine operation of the high-endurance cutters was considered. The principle behind this type of operation is as follows: At slow ship speeds, the main diesel engines are forced to operate at slow speed-low load conditions, resulting in high brake specific fuel consumption (BSFC). Transferring propulsion to a single engine would shift the operating point to a higher speed-load condition at the same ship speed, thus reducing BSFC but increasing the total fuel consumption of that engine. Single-engine operation would then be advantageous if total fuel consumption was less than the total for two-engine operation.

Single-engine operation has, in fact, been used by WHEC's, although not specifically for a reduction in fuel consumption and primarily at the discretion of the commanding officer. The usual procedure was to allow the unused propeller to freewheel at full-ahead pitch, disengaging it after it had been in operation. The propeller continued to rotate, but it was reported that, if the ship slowed to the point where the free propeller stopped, it would not start to rotate once the ship got underway again. WHEC's were reputed to achieve 10.5 knots on one screw at an engine speed of 660 RPM, but at unknown pitch.

The propeller diagrams for both Escher-Wyss and PSI designs were modified for single-engine operation with considerations for a trailing (rotating) and a locked propeller shaft (Appendix A). Fuel consumption data were analyzed throughout the permissible operating range to determine if, and when, single engine operation was feasible.

6. DISCUSSION OF RESULTS

6.1 MEDIUM-ENDURANCE CUTTER (WMEC) DUTY CYCLE DATA

The data from the duty cycle recorder systems for the medium-endurance cutters VALIANT, DURABLE, and DECISIVE are presented in Tables 6-1 through 6-3. While analyzing the charts from the recorders, it was observed that all of the WMEC's showed only minor redistribution of the percentage time spent in each operating position from month to month, though there were monthly variations in total running time.

In general, both engines of a ship operated primarily in the same range of throttle positions, but the individual modal percentages varied somewhat between the two engines of each vessel; this situation could have been due to either an imbalance in engine power output or because of the fact that the WMEC's frequently operated on one engine. The DURABLE and the DECISIVE, respectively, logged 23% more time on the port engine; the times for the VALIANT differed by only 4%. Additionally, the most commonly used throttle positions varied among the ships. For example, the DECISIVE operated principally in positions 3 to 4 1/2, while the DURABLE employed positions 6 to 6 1/2 most frequently (Tables 6-2 and 6-3). The primary throttle positions employed by the cutters and the time spent in that range are summarized in Table 6-4.

A set of time-based modal factors was generated for the WMEC's by summing the operating time for both engines in a particular operating mode and computing the percentage of total operating time that this represented. These results are summarized in Table 6-5. The modal weighting factors indicate that the vast majority of the combined operating time (78%) was spent in handle positions 3 to 6 1/2 and half of the remainder was spent at Idle. Handle positions 8 and 1 to 1 1/2 were, for all practical purposes, unused.

TABLE 6-1.   DUTY CYCLE MODES AND TIMES -- WMEC VALIANT

January 1 - September 5, 1976

Throttle Position	Port Engine		Starboard Engine	
	Hours	%	Hours	%
0 (Idle)	91.1	10	79.0	8
1 to 1 1/2	1.4	0	2.7	0
2 to 2 1/2	48.4	5	47.9	5
3 to 3 1/2	127.2	14	110.9	12
4 to 4 1/2	227.8	24	281.5	29
5 to 5 1/2	52.1	6	111.2	12
6 to 6 1/2	311.2	34	246.5	26
7 to 7 1/2	62.8	7	64.5	7
8	Nil	0	6.9	1
Totals	992.0	100	951.9	100

TABLE 6-2.   DUTY CYCLE MODES AND TIMES -- WMEC DECISIVE

October 19, 1976 - June 28, 1977

Throttle Position	Port Engine		Starboard Engine	
	Hours	%	Hours	%
0 (Idle)	116.9	11	121.6	9
1 to 1 1/2	28.6	3	15.9	1
2 to 2 1/2	108.4	10	49.7	3
3 to 3 1/2	381.1	35	371.8	27
4 to 4 1/2	252.2	23	480.4	34
5 to 5 1/2	121.8	11	262.6	19
6 to 6 1/2	72.1	6	95.8	7
7 to 7 1/2	6.4	1	1.3	0
8	0.5	0	Nil	0
Totals	1088.0	100	1399.1	100

TABLE 6-3.   DUTY CYCLE MODES AND TIMES -- WMEC DURABLE

April 11 - September 1, 1976

Throttle Position	Port Engine		Starboard Engine	
	Hours	%	Hours	%
0 (Idle)	122.7	16	93.6	15
1 to 1 1/2	2.4	0	6.0	1
2 to 2 1/2	22.6	3	24.6	4
3 to 3 1/2	50.0	6	38.0	6
4 to 4 1/2	57.8	7	45.3	7
5 to 5 1/2	85.3	11	104.3	16
6 to 6 1/2	258.9	32	328.8	51
7 to 7 1/2	191.2	25	1.0	0
8	Nil	0	Nil	0
Totals	790.9	100	641.6	100

TABLE 6-4.   PRINCIPAL THROTTLE POSITION USE -- WMEC

Ship	Average Monthly Operating Time	Throttle Position	% TIME	
			Port	Starboard
	(Port-Starboard)			
VALIANT	(115-120) hr/mo	3 to 6 1/2	78%	79%
DURABLE	(160-130) hr/mo	4 to 6 1/2	50%	74%
DECISIVE	(135-175) hr/mo	3 to 5 1/2	69%	80%

TABLE 6-5. AVERAGE TIME-BASED MODAL WEIGHTING FACTORS -- WMEC

Throttle Position	Valiant		Durable		Decisive		Total	Modal Weighting Factor
	Port (hrs)	Stbd. (hrs)	Port (hrs)	Stbd. (hrs)	Port (hrs)	Stbd. (hrs)	(hrs)	
0 (Idle)	91.1	79.0	122.7	93.6	116.9	121.6	624.9	0.11
1 to 1 1/2	1.4	2.7	2.4	6.0	28.6	15.9	57.0	0.01
2 to 2 1/2	4?.4	47.9	22.6	24.6	108.4	49.7	302.0	0.05
3 to 3 1/2	127.2	110.9	50.0	38.0	381.1	371.8	1079.0	0.19
4 to 4 1/2	227.8	2?1.5	57.8	45.3	252.2	480.4	1345.0	0.23
5 to 5 1/2	52.1	111.2	85.3	104.3	121.8	262.6	737.3	0.13
6 to 6 1/2	311.2	246.5	258.9	328.3	72.1	95.8	1312.8	0.23
7 to 7 1/2	62.8	64.5	191.2	1.0	6.4	1.3	327.2	0.06
8	Nil	6.9	Nil	Nil	0.5	Nil	7.4	Nil
Totals	-	-	-	-	-	-	5792.6	1.0

6.2 HIGH-ENDURANCE CUTTER (WHEC) DUTY CYCLE DATA

The WHEC duty cycle data obtained from the on-board recording system were sup-
plemented by information extracted from engine room logs, which contained a record of
bell orders (mode changes) received from the bridge. These records were, however,
found to be incomplete or at least ambiguous concerning important details. The find-
ings are summarized below:

a. The bell order record was kept when the engines were on engine room control,
but not when pilot house control was used.

b. Recorded bell orders by themselves were insufficient to allow the amount of
engine idle time to be determined. However, discrepancies were partially
resolved by inspection of the watch officer's log entries for comments con-
cerning the times that an engine was secured (stopped) and restarted.

c. There were instances when the engines were on engine room control, but there
occurred a rapid series of bell orders from the bridge. The analysis of such
a situation adds greatly to the total analytical time, yet adds little useful
information since the operating time involved is usually short compared to
the total engine operating time. Therefore, these situations were skipped
over without significantly degrading the data.

The actual duty cycle data which were extracted from the engine room logs of the
WHEC's CHASE and GALLATIN are shown in Tables 6-6 and 6-7. In general, the distribution
of time between engine room control and pilot house control, and among the various
engine modes, was relatively constant even though total monthly operating time varied
greatly. The majority (80-85%) of the operating time was spread over 1/3, 2/3, and
Standard modes, with the Standard condition receiving the higher use. Idle time was
usually less than 10% of the total, while the combined operating time at Flank and
Full was usually less than 10%. A summary of the combined log book data is presented
in Table 6-8, which confirms the general remarks given here. During the 10-month
period studied, each engine operated an average of 261 hours per month, which cor-
responds to about eleven (11) days per month, a time utilization factor of approximate-
ly 36%. Based on maximum engine power output of 3600 brake horsepower at full speed,
and using the average percentages for the combined data, a power utilization factor
of 46.0% was calculated for the WHEC main diesel engines. A cycle composite brake
specific fuel consumption (BSFC) of 0.397 pounds per brake horsepower-hour was computed
based on the engine manufacturer's published BSFC values for each operating mode.

The duty cycle recording system results for the WHEC's CHASE and HAMILTON are
shown in Table 6-9. Data from the CHASE followed essentially the same monthly pattern
as did the log book data, but a slight deviation from log book data was noted as engine
operation was primarily at 1/3 and 2/3, while Standard condition occupied most of the
remaining portion. Operation at Full was slight, and little or no time was recorded
at Idle and Flank speeds. Average monthly operation was almost 300 hours per engine.
Total accumulated hours for the two engines were within two percent, and the percentage
time spent in each mode by each engine was very nearly equal.

In contrast to the CHASE, the HAMILTON accumulated a significant amount of Flank
operating mode (42% to 45%). It is possible that this type of operation may have been
peculiar to a specific mission and, as such, is not indicative of normal operating
conditions. Other patterns are similar to the CHASE in that percentage time in each
mode for each engine and total accumulated time for the two engines was almost equal.
However, total recorded operating time for the six-month data acquisition period was
less than 300 hours; this very low utilization is due to the fact that the HAMILTON
was in port for several months for maintenance. After the ship returned to duty,
problems arose with the instrumentation so that little usable data was returned to
SwRI for analysis.

The time-based modal factors for the high-endurance cutters were computed from
information taken from the duty cycle recorders on-board the CHASE. This was deemed
to be the most extensive and most accurate data available. The resulting factors are
shown in Table 6-10 and reflect the trends described previously for the CHASE.

TABLE 6-6. LOG BOOK DUTY CYCLE DATA - WHEC CHASE

Period Covered	Port Engine		Starboard Engine	
	Hours	%	Hours	%
AUGUST 1975				
Total Operating Time	403.7	100	390.7	100
Engine Room Control	278.5	69	265.5	68
Pilot House Control	125.2	31	125.2	32
Engine Mode				
Idle	20.2	7	25.7	10
1/3	89.5	32	80.0	30
2/3	27.3	10	26.4	10
Standard	133.1	48	125.0	47
Full	8.4	3	8.4	3
Flank	Nil	0	Nil	0
Totals	278.5	100	265.5	100
OCTOBER 1975				
Total Operating Time	183.5	100	187.6	100
Engine Room Control	156.0	85	160.1	85
Pilot House Control	27.5	15	27.5	15
Engine Mode				
Idle	17.5	11	16.6	10
1/3	30.1	20	33.0	21
2/3	29.6	19	30.8	19
Standard	78.5	50	79.4	50
Full	0.3	0	0.3	0
Flank	Nil	0	Nil	0
Totals	156.0	100	160.1	100
NOVEMBER 1975				
Total Operating Time	194.8	100	195.1	100
Engine Room Control	164.1	84	164.4	84
Pilot House Control	30.7	16	30.7	16
Engine Mode				
Idle	17.2	10	15.0	9
1/3	13.8	8	16.8	10
2/3	12.6	8	11.0	6
Standard	116.9	71	118.0	72
Full	1.0	1	1.0	1
Flank	2.6	2	2.6	2
Totals	165.1	100	164.4	100

TABLE 6-7. LOG BOOK DUTY CYCLE DATA - WHEC GALLATIN

Period Covered	Port Engine		Starboard Engine	
	Hours	%	Hours	%
SEPTEMBER 1975				
Total Operating Time	186.0	100	215.6	100
Engine Room Control	171.6	92	201.2	93
Pilot House Control	14.4	8	14.4	8
Engine Mode				
Idle	16.8	10	14.1	7
1/3	34.0	20	36.8	18
2/3	32.2	19	55.4	28
Standard	68.4	40	74.8	37
Full	15.5	9	15.4	8
Flank	4.7	2	4.7	2
Totals	171.6	100	201.2	100
OCTOBER 1975				
Total Operating Time	301.5	100	351.7	100
Engine Room Control	287.0	95	337.2	96
Pilot House Control	14.5	5	14.5	4
Engine Mode				
Idle	13.1	4	16.4	5
1/3	36.2	13	17.6	5
2/3	79.5	28	70.4	21
Standard	135.1	47	209.8	62
Full	19.7	7	19.6	6
Flank	3.4	1	3.4	1
Totals	287.0	100	337.2	100

TABLE 6-8a. SUMMARY OF LOG BOOK DUTY CYCLE DATA FOR WHEC -- FIVE CUTTER-MONTHS OF OPERATION

	Port Engine Average		Starboard Engine Average	
	Hours	%	Hours	%
Total Operating Time	253.9	100	268.1	100
Engine Room Control	211.4	83	225.7	84
Pilot House Control	42.5	17	42.5	16
Engine Mode				
Idle	17.0	8	17.6	8
1/3	40.7	20	36.8	16
2/3	36.2	17	38.8	17
Standard	106.4	50	121.4	54
Full	9.0	4	9.0	4
Flank	2.1	1	2.1	1
Totals	211.4	100	225.7	100

TABLE 6-8b. OVERALL AVERAGE PER MONTH

	Total Operation for 10 Engine-Months	
	Hours	%
Total Operating Time	261.0	100
Engine Room Control	218.5	84
Pilot House Control	42.5	16
Engine Mode		
Idle	17.3	8
1/3	38.7	18
2/3	37.5	17
Standard	113.9	43
Full	9.0	4
Flank	2.1	1
Totals	218.5	100

6-8

TABLE 6-9a. DUTY CYCLE MODES AND TIMES -- WHEC CHASE TAKEN FROM DUTY CYCLE RECORDER SYSTEM

March 15 - August 20, 1976

Engine Mode	Port Engine		Starboard Engine	
	Hours	%	Hours	%
Idle	0.1	0	0.3	0
1/3	497.6	33	462.9	32
2/3	550.8	37	555.0	38
Standard	334.3	23	334.6	23
Full	105.9	7	104.9	7
Flank	Nil	0	Nil	0
Totals	1488.7	100	1457.7	100

TABLE 6-9b. DUTY CYCLE MODES AND TIMES -- WHEC HAMILTON TAKEN FROM DUTY CYCLE RECORDER SYSTEM

October 19, 1976 - April 15, 1977

Engine Mode	Port Engine		Starboard Engine	
	Hours	%	Hours	%
Idle	2.4	1	0.8	0
1/3	34.3	12	20.1	8
2/3	54.2	19	49.0	19
Standard	41.3	15	45.5	17
Full	29.8	11	30.2	11
Flank	120.0	42	117.4	45
Totals	282.0	100	263.0	100

TABLE 6-10. WMEC TIME-BASED MODAL WEIGHTING FACTORS

Engine Mode	% of Total Operating Time
Idle	0
1/3	32.5
2/3	37.5
Standard	23
Full	7
Flank	0
Total	100

6.3 WIND CLASS ICEBREAKER (WAGB) DUTY CYCLE DATA

Duty cycle data from the Icebreaker WESTWIND are shown in Table 6-11. No data were available for engine 2A due to a recorder problem, which was compounded when the 2A generator failed. It should be pointed out at this time that the WESTWIND was damaged and underwent drydock repairs during the icebreaking season; this precluded obtaining data during such operation. The project was terminated before the next icebreaking season, so that the data given here represents operation in open-water conditions during a North Sea cruise.

From Table 6-11, it can be seen that operating time and percentages varied some-what among the modes for the three engines; these variations are believed to occur for three reasons. First, some of the data from the recorder charts fell between two modes. As a result, the data grouping was determined by establishing arbitrary toler-ance bands around the recorded parameters, which introduced a degree of uncertainty in the analysis. The second factor causing time variations among the modes was the de-sire to keep the two propeller shafts rotating at the same designated speed and the engines producing equal power for each shaft. Adjustment of individual engine operat-ing modes was required to obtain this balanced condition with the diesel-electric propulsion system; therefore, engines on the same shaft can be compared, but not en-gines on opposite shafts.[7] Third, in an effort to reduce fuel consumption, the ice-breaker regularly operated on just two of the four engine/generator sets, using one set per propeller. This increased the load on each engine and caused them to operate at a lower BSFC. Total operating time was balanced by alternating the two engines used in this manner.

The data indicated that a significant amount of time was spent in the Full and Flank modes. This was probably due to the fact that the icebreaker was on an extended cruise in the North Atlantic and was not engaged in any icebreaking activity. The 2/3 mode received only minor use, and the remainder of the operating time was evenly dis-tributed among idle, 1/3, and Standard. Since the data do not include icebreaking activities and represent a relatively short operating period for a single cutter, these observations cannot be used to generalize icebreaker operation.

6.4 MEDIUM-ENDURANCE CUTTER PROPELLER PITCH/ENGINE PERFORMANCE ANALYSIS

Fuel consumption of the WMEC's (in terms of pounds per hour per engine and gallons per nautical mile per engine) and the percentage increase in each quantity from the minimum value for a given ship speed were calculated for points throughout the cutter speed and propeller pitch ranges. Basic data and results of these computations are presented in Appendix B. These engine fuel consumption figures have been mapped onto the propeller diagram in Figure 6-1 as a function of cutter speed and propeller pitch.
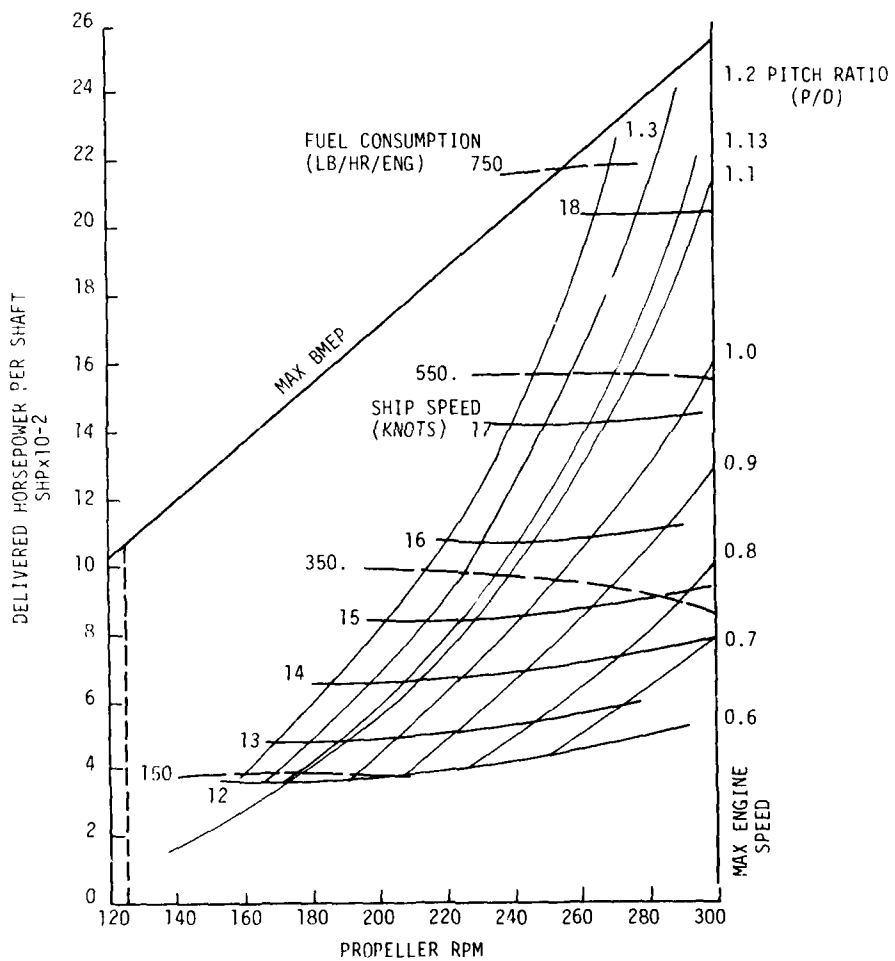
FIGURE 6-1. WMEC PROPELLER DIAGRAM WITH FUEL CONSUMPTION

TABLE 6-11. DUTY CYCLE MODES AND TIMES -- WAGB WESTWIND

March 18

Engine Mode	Engine 1A		Engine 2A		Engine 1B		Engine 2B	
	Hours	%	Hours	%	Hours	%	Hours	%
Idle	59.3	10	— —	——	69.9	11	76.0	12
1/3	19.3	4	——	——	73.7	13	63.0	10
2/3	32.3	5	—	—	35.3	6	23.2	4
Standard	50.2	9	——	——	89.1	16	101.2	17
Full	237.9	40	——	——	132.2	23	191.5	32
Flank	190.2	32			176.7	31	153.0	25
Totals	589.2	100	——	——	571.9	100	608.0	100

Several trends in the WMEC data are evident. First, a small increase in ship speed required a large increase in fuel consumption, regardless of the pitch ratio. Second, for any given ship speed, as the pitch ratio increased, fuel consumption decreased until it reached a minimum value at the two or three highest pitch ratios. Finally, fuel consumption became much more sensitive to changes in pitch as ship speed was reduced. Even though data were not available for low ship speeds, it was assumed that these trends extended into this region.

Referring to the propeller diagram (Figure 6-1) and to Figures 6-2 and 6-3, fuel consumption savings are possible for the WMEC without sacrificing ship speed. Movement of the operating point within the envelope bounded above by a const nt fuel rate and below by a constant ship speed line, and which intersects at the original operating point, would produce a reduction in fuel usage as well as a possible increase in cutter speed. For example, the operating point Figure 6-1 defined by

285 SRPM

15 Knots

0.85 Pitch Ratio

350 lb/hr/eng Fuel Consumption

could be shifted to the left along the constant ship speed line of 15 knots to a higher pitch ratio of 1.3, thus reducing fuel consumption by approximately 50 lb/hr/eng. However, the most dramatic decrease in fuel consumption results from shifting an operating point vertically down the propeller diagram by holding engine speed constant and reducing the propeller pitch. Unfortunately, this also results in a significant penalty in ship speed.

A cycle composite fuel consumption value was calculated for the medium-endurance cutters based upon the parameters given above and the WMEC time-based modal factors; it is presented in Table 6.12a. Also, a second optimized cycle composite fuel consumption (Table 6.12b) was computed according to the following assumptions. First, operating mode changes are made at constant ship speed. Second, for all ship speeds, an increase in pitch reduces fuel consumption throughout the operating range. Last, the maximum design pitch, as shown on the propeller diagram, can be obtained during diesel engine operation in the region where maximum engine torque or brake mean effective pressure (BMEP) is not exceeded. Mode changes were limited to the constant ship speed condition since it was believed that, when a specific mode was called for, a certain cutter speed was actually desired. Further, it is already known that fuel consumption savings are possible by operating at slower speed conditions.
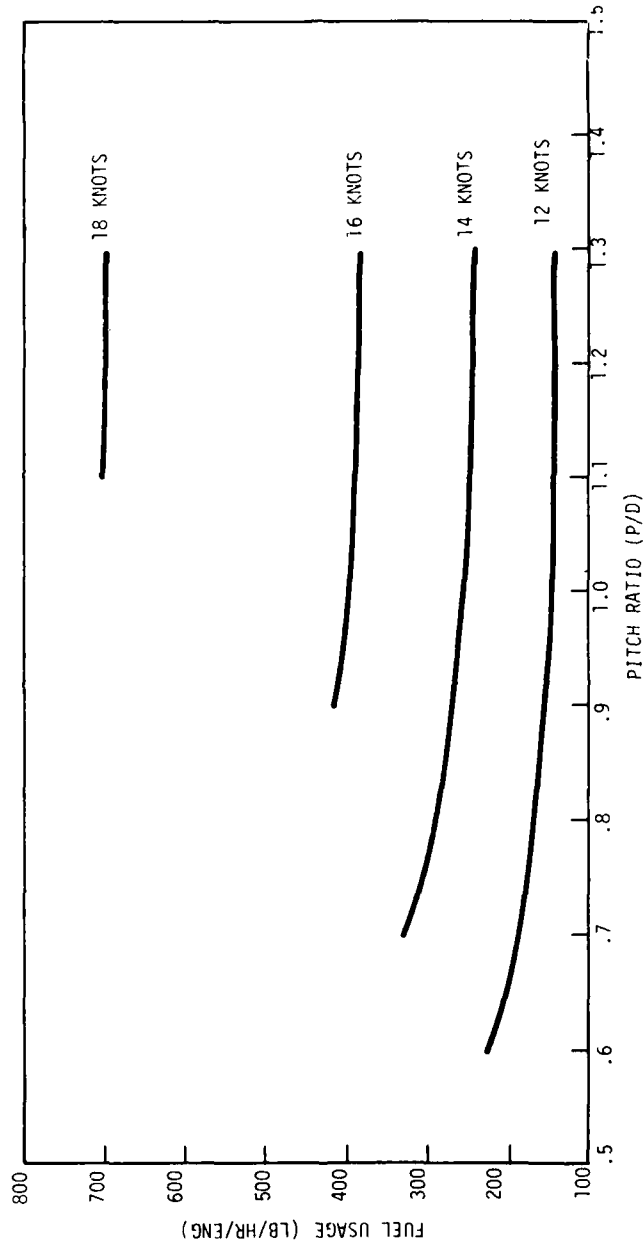
FIGURE 6-2. EFFECT OF PITCH RATIO ON FUEL CONSUMPTION -- USCG 210B WMEC
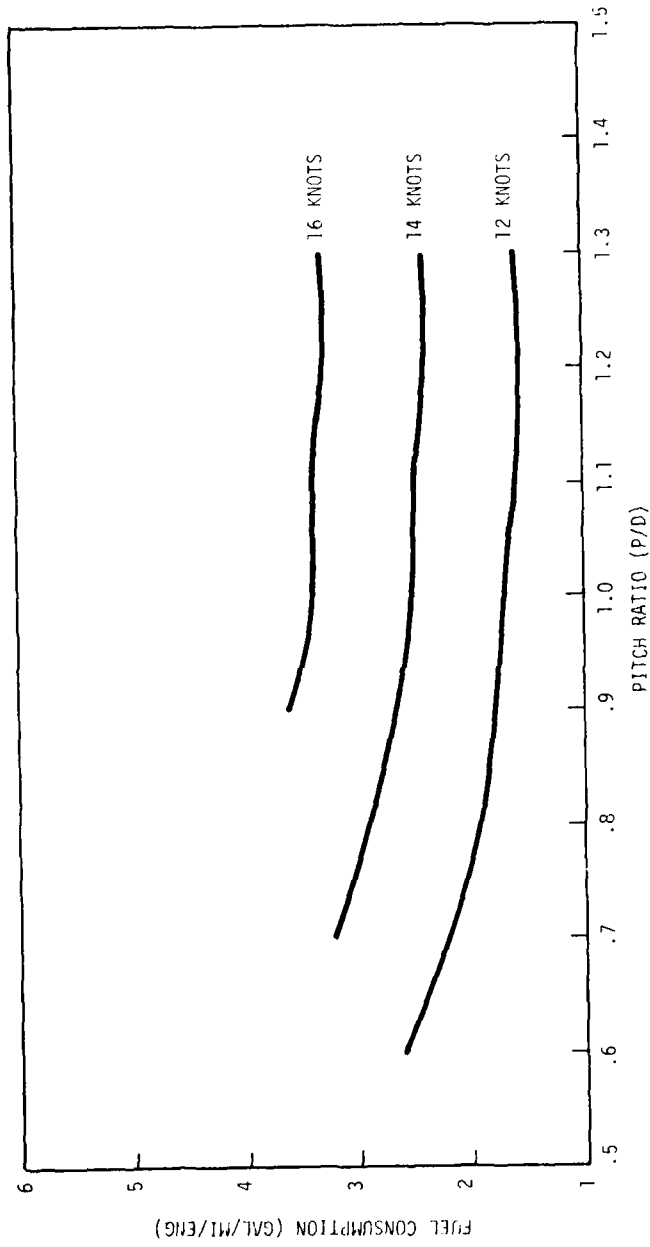
FIGURE 6-3. EFFECT OF PITCH RATIO ON FUEL CONSUMPTION -- USCG 210B WMEC

TABLE 6-12a. CYCLE COMPOSITE FUEL CONSUMPTION -- 210B WMEC

Throttle Position	Ship Speed (Knots)	Modal Weight Factor	(P/D) Pitch Ratio	Engine RPM	BHP/cyl	BSFC lb/BHP-hr	Fuel Consumption		Weighted Fuel Consumption	
							lb/hr/eng	gal/mi/eng	lb/hr/eng	gal/mi/eng.
0	0	0.11	0	480	-	-	36	-	4.0	-
1	1.6	0.01	.23	480	2	-	36	3	0.4	.03
2	3.3	0.05	.48	480	3.3	.68	36	1.2	1.5	.06
3	5	0.19	.71	480	5	.45	36	1.0	6.8	.19
4	8	0.23	.95	525	8.8	.43	60.2	1.0	13.8	.24
5	13.2	0.13	1.13	640	31.9	.380	193.8	2.1	25.2	.27
6	15	0.23	1.13	750	51.6	.365	301.1	2.8	69.3	.64
7	17.1	0.06	1.13	875	90	.354	510.4	4.2	30.6	.25
8	18.3	0	1.13	1000	144	.342	787	6.0	0	0
Totals	-	1.0	-	-	-	-	-	-	151.6	1.68

TABLE 6-12b. OPTIMIZED CYCLE COMPOSITE FUEL CONSUMPTION -- 210B WMEC

Throttle Position	Ship Speed (Knots)	Modal Weight Factor	(P/D) Pitch Ratio	Engine RPM	BHP/cyl	BSFC lb/BHP/hr	Fuel Consumption		Weighted Fuel Consumption	
							lb/hr/eng	gal/mi/eng	lb/hr/eng	gal/mi/eng
0	0	0.11	0	480	0	-	36	-	4.0	-
1	1.6	0.01	.23	480	2	-	36	3	0.4	.03
2	3.3	0.05	.48	480	3.3	.68	36	1.2	1.5	.06
3	5	0.19	.71	480	5	.45	36	1.0	6.8	.19
4	8	0.23	1.05	480	8.8	.43	60.2	1.0	13.8	.24
5	13.2	0.13	1.3	557	31.6	.375	189.4	2.0	24.6	.26
6	15	0.23	1.3	677	51.3	.364	298.5	2.8	68.7	.64
7	17.1	0.06	1.3	800	89.4	.352	503.3	4.2	30.2	.25
8	18.3	0	1.3	933	143.8	.342	787	6.0	0	0
Totals	-	1.0	-	-	-	-	-	-	150.0	1.67

The final assumption in the set may not be true; the WMEC may not be able to achieve maximum pitch with diesel engine operation. At present, the WMEC's operate at a maximum pitch ratio of 1.13, well below the design specification value of 1.3. The maximum design pitch specification was the value at which a physical stop was placed in the amount of blade rotation; it was not meant to be an operating point and is not an indicator of the maximum pitch that the engines can handle. Also, these propellers were designed for the 210A's gas turbine operation.[7] The diesel engines may not be able to supply the power necessary to turn the propellers at higher pitch and reduced rotational speed. Referring to the propeller diagram, as pitch increases at constant ship speed there is actually a slight reduction in the required shaft horsepower, but a large decrease in shaft speed. Consequently, the engines are forced to produce nearly the same power output at a considerably reduced engine speed. Determination of the actual maximum usable pitch would require cutter testing throughout the cutter's speed range. Therefore, the actual and the optimum cycle composite fuel consumption figures represent extremes, and any improvement in fuel consumption is expected to lie between the values given.

The resulting decrease in fuel consumption through optimization of the pitch schedule amounted to only one percent for the WMEC's, as shown in Table 6.12b. As previously observed, at the two or three highest pitch settings fuel consumption was at an essentially constant minimum value. Since operation was either in or very near to this region, only slight benefits were gained solely by increasing pitch and maintaining ship speed. Larger decreases in the cycle composite fuel consumption were possible, but only at the sacrifice of cutter speed (moving an operating point vertically down the propeller diagram). A more practical solution would be to adopt slower ship speed operating practices than to alter the pitch schedule.

6.5 HIGH-ENDURANCE CUTTER PROPELLER PITCH/ENGINE PERFORMANCE ANALYSIS

6.5.1 Normal (Two-Propeller) Operation

Fuel consumption calculations for the high-endurance cutters were handled in a manner identical to the medium-endurance cutters. Again, these calculations should be looked upon as an approximation of the actual fuel consumption because of the accuracy of the available data. The propeller diagram which relates propeller pitch and speed to ship speed is a theoretical estimate of propeller performance used for design purposes; as such, it may not be an accurate assessment of actual cutter performance. Comparing the propeller diagrams (Figures 6-6 and 6-7) to available WHEC performance data (shown in Table 6-13), significant differences were found. The performance data indicates that ships are operating more efficiently than the propeller diagrams predict because either the propellers are more efficient than design data indicates, or the ships have much less resistance than shown on the resistance curve. Either the corrected propeller diagram is in error, in which case the source of error is either the original Escher-Wyss propeller diagram or the resistance curve (see report in Appendix A), or the performance data in Table 6-13 are wrong. Accurate WHEC performance data must be obtained to clarify the discrepancy.

TABLE 6-13. WHEC PERFORMANCE DATA TAKEN FROM SHIP INSTRUMENTATION

Pitch Ratio (P/d)	Shaft RPM	Ship Speed (Knots)
0.5	75	5
1.0	75	9.8 - 10
1.0	120	15
1.0	135	16.5
1.0	150	17.8 - 18.2

Due to the lack of accurate data at slow ship speeds (less than 100 knots) an approximation was made of low-speed fuel consumption. Even though the total fuel consumption in this region is not a major significance, a small change in the operating condition produces a large change in the weighted or cycle composite fuel consumption.

Despite the above discrepancies, the data are of value in evaluating relative changes in cutter operating procedures, but should not be interpreted as an absolute-value estimate of ship fuel consumption. The tabulated fuel consumption figures are presented in Appendix B and summarized in Figures 6-4 and 6-5. Fuel consumption data plotted on the propeller diagram facilitated the analysis of pitch schedule alterations (Figures 6-6 and 6-7). In this regard, the trends observed with the WMEC's also pertained to the WHEC's due to the similarity of the propeller diagrams. Small increases in ship speed required a large increase in fuel consumption, and as pitch ratio increased at a given ship speed, fuel consumption decreased such that a reduction in fuel consumption was possible without sacrificing cutter performance. Alternately, decreasing shaft horsepower (moving vertically down the propeller diagram) resulted in the most significant fuel conservation, but also decreased ship speed.

Cycle composite fuel consumption calculations (Tables 6-14 and 6-15), which were based on the assumptions used for the WMEC's, indicated that fuel savings were possible only in two modes (Standard and Full) when pitch schedule alterations were limited to constant ship speed in each mode. The operating modes 2/3, 1/3, and Idle are at the engine idle speed, and any increase in pitch would result in increased ship speed. The remaining condition, Flank, which represents the non-functional handle positions above eighth position, had a modal weighting factor of zero and did not contribute to the cycle composite fuel consumption.

The resulting decrease in fuel usage was 2.4% and 12% for ships equipped with PSI and Escher-Wyss propellers, respectively. It was assumed that a maximum pitch ratio of 1.4 could be attained in the Standard and Full modes. This is a substantial increase from the maximum pitch ratio of 1.0 which is presently employed, and the ships may, in fact, be unable to achieve this setting. Based on the fuel consumption figures, it appears that the pitch schedule could be re-programmed for minimum fuel consumption throughout the operating range by utilizing the maximum attainable pitch at each engine speed. It is conceivable that the maximum design pitch of 1.4 cannot be obtained at some engine speeds and that the maximum usable pitch may vary throughout the engine speed range. A hypothetical pitch schedule which assumes a maximum usable pitch of 1.4 would consist of three segments when drawn on the propeller diagram (Figures 6-8 and 6-9). First, the pitch schedule would progress vertically up the constant engine idle speed line until a pitch ratio of 1.4 was encountered. Second, the point would move up the 1.4 pitch-ratio line to the intersection with maximum BMEP. The final segment would then consist of the maximum BMEP line up to rated engine speed and load.

It should be pointed out that, at present, ships equipped with Escher-Wyss propellers consume approximately 14% less fuel on a cycle composite basis than those equipped with PSI props. As was mentioned in the propeller diagram correction report (Appendix A), the PSI propeller has a lower efficiency relative to the Escher-Wyss. This also accounts for the small decrease in cycle composite fuel consumption available with the PSI design when pitch is increased at constant ship speed.

6.5.2 Single-Engine Operation

Single-engine operation fuel consumption data were extracted from the propeller diagrams and the engine performance map, and are included in Appendix C. This analysis involved four cases -- ships equipped with Escher-Wyss or PSI propellers, each operating with a trailing (rotating) or locked propeller shaft. Again, these data were added to the propeller diagrams (Figures 6-10 to 6-13) for ease of analysis and are shown in Figures 6-14 through 6-17.

Comparing the propeller diagrams for one- and two-engine operation, it was observed that the horsepower required to produce a given ship speed was at a minimum in the mid-pitch ratio range (1.0 - 1.2) for single-engine operation and in the two or three highest pitch settings under normal two-engine operation. This would be expected since conversion to single-engine operation essentially doubles the thrust from one propeller, requiring a reduction in pitch and an increase in shaft speed to maintain ship speed. Since fuel consumption and horsepower decrease when moving vertically down the propeller diagram, minimum fuel consumption at each ship speed is at the point of minimum horsepower. Therefore, preferred operation with two engines would be at the highest achievable pitch, and with one engine, at a slightly lower pitch.
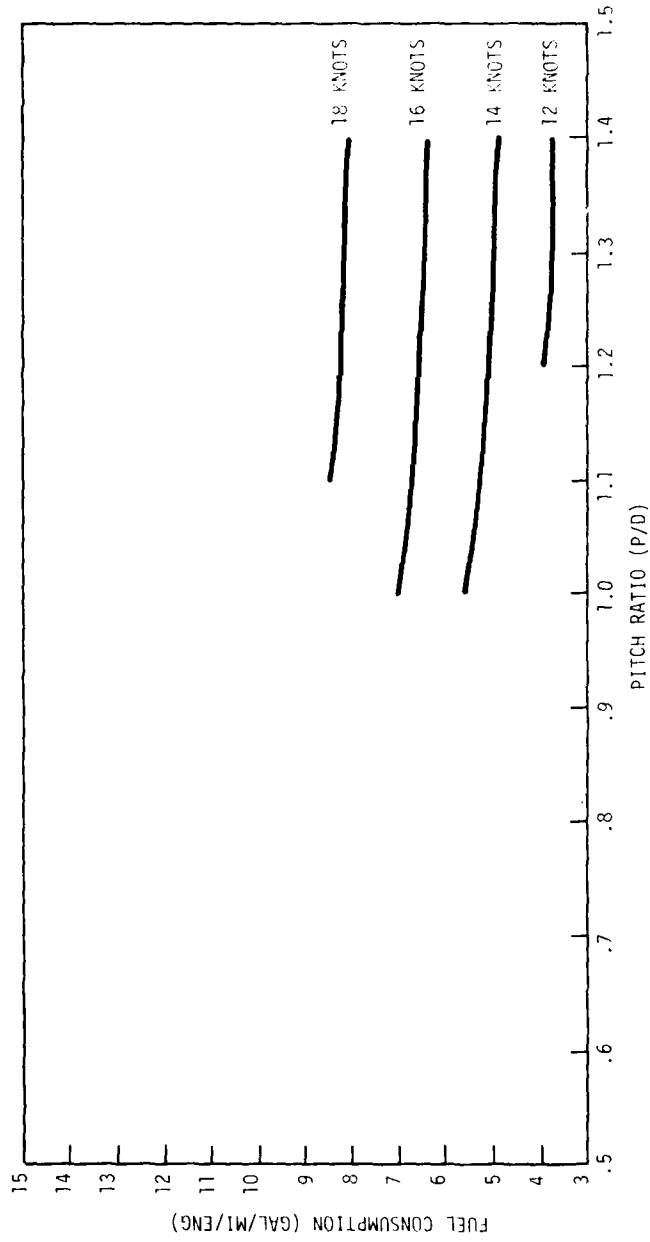
FIGURE 6-4. WHEC FUEL VOLUME FLOW RATE, ESCHER-WYSS ® PROPELLER

6-18

WHEC FUEL VOLUME FLOW RATE, PROPULSION SYSTEMS, INC., ® PROPELLER

18 KNOTS

16 KNOTS

14 KNOTS

12 KNOTS

PITCH RATIO (P/D)

FUEL CONSUMPTION (GAL/MI/ENG)

.5   .6   .7   .8   .9   1.0   1.1   1.2   1.3   1.4   1.5

3   4   5   6   7   8   9   10   11   12   13   14   15
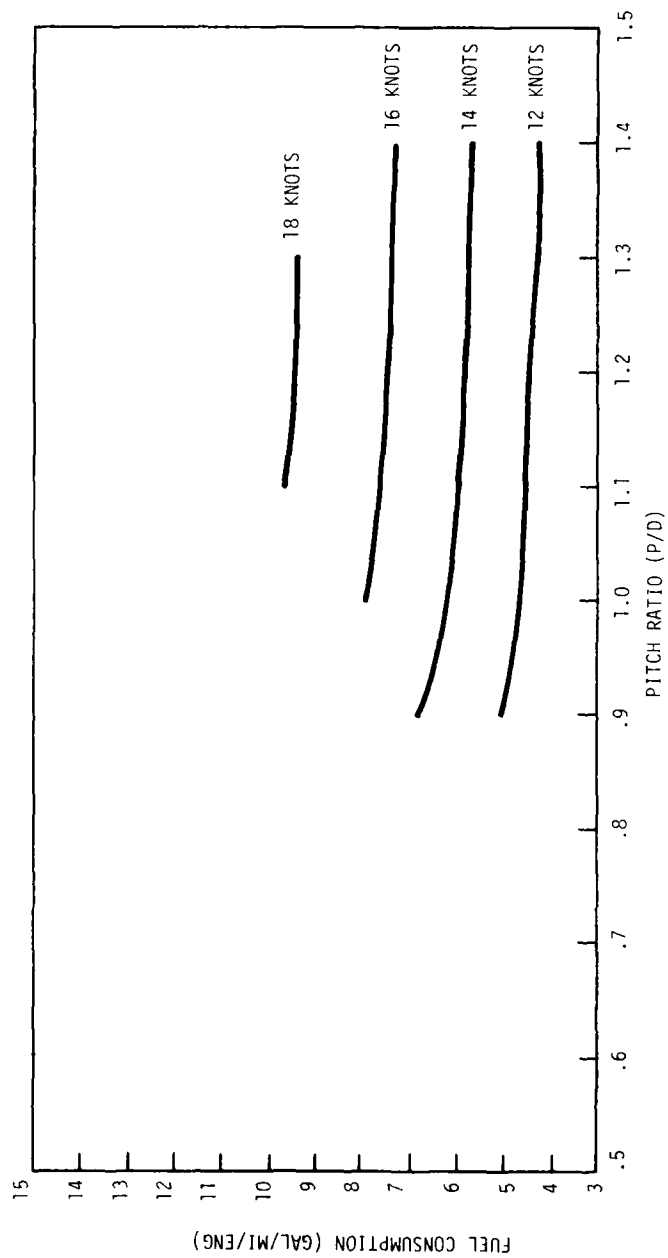
FIGURE 6-5.   WHEC FUEL VOLUME FLOW RATE, PROPULSION SYSTEMS, INC., ® PROPELLER
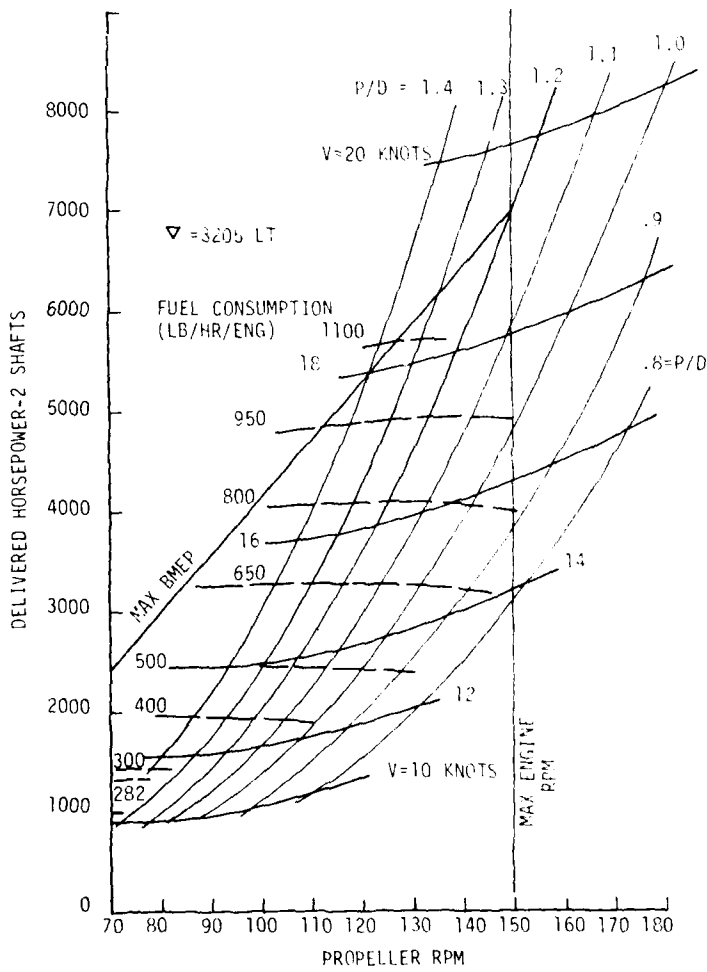
FIGURE 6-6. WHEC PROPELLER DIAGRAM WITH FUEL CONSUMPTION, ESCHER-WYSS ® PROPELLER
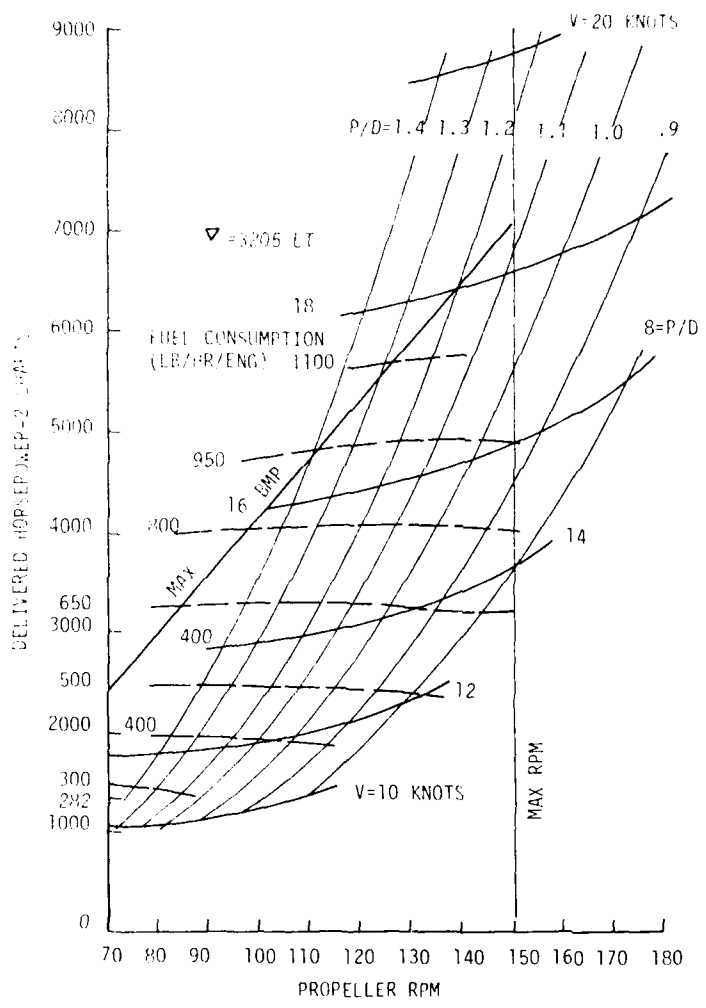
FIGURE 6-7.   WHEC PROPELLER DIAGRAM WITH FUEL CONSUMPTION, PROPULSION SYSTEMS,
INC. ® PROPELLER

TABLE 6-14a. CYCLE COMPOSITE FUEL CONSUMPTION -- WHEC ESCHER-WYSS ® PROPELLER

Mode	Ship Speed (Knots)	Modal Weight Factor	(P/D) Pitch Ratio	Engine RPM	BHP/cyl	lb/BHP-hr	Fuel Consumption		Weighted Fuel Consumption	
							lb/hr/eng	gal/mi/eng	lb/hr/eng	gal/mi/eng.
Idle	0	0	0	450	0	–	–	–	–	–
1/3	4	.325	.55	450	8	0.8	76.8	2.2	25	0.7
2/3	8	.375	1.0	450	20	.460	117	3.1	66.2	1.15
Standard	14	.23	1.0	750	114	.409	560	5.6	129	1.29
Full	17	.07	1.0	900	203	.388	945	7.75	66	0.54
Flank	17	0	1.0	900	203	.388	945	7.75	0	0
Totals	–	1.0	–	–	–	–	–	–	286.2	3.68

TABLE 6-14b. OPTIMIZED FUEL CONSUMPTION -- WHEC ESCHER-WYSS PROPELLER

Mode	Ship Speed (Knots)	Modal Weight Factor	(P/D) Pitch Ratio	Engine RPM	BHP/cyl	lb/BHP-hr	Fuel Consumption		Weighted Fuel Consumption	
							lb/hr/eng	gal/mi/eng	lb/hr/eng	gal/mi/eng
Idle	0	0	0	450	–	–	–	–	–	–
1/3	4	.325	.55	450	8	0.8	76.4	2.7	25.1	0.67
2/3	8	.375	1.0	450	20	.460	110.4	1.9	41.4	0.72
Standard	14	.23	1.4	560	104	.403	502.9	5.0	115.7	0.15
Full	17	.07	1.4	690	184	.392	865.5	7.1	60.5	.495
Flank	19.5	0	1.22	900	300	.387	1360.8	9.7	0	0
Totals	–	1.0	–	–	–	–	–	–	242.4	3.24

TABLE 6-15a. CYCLE COMPOSITE FUEL CONSUMPTION -- WHEC PROPULSION SYSTEMS INC. ® PROPELLER

Mode	Ship Speed (Knots)	Modal Weight Factor	(P/D) Pitch Ratio	Engine RPM	BHP/cyl	lb/BHP-hr	Fuel Consumption		Weighted Fuel Consumption	
							lb/hr/eng	gal/mi/eng	lb/hr/eng	gal/mi/eng.
Idle	0	0	0	450	-	-	-	-	0	0
1/3	5	.325	.53	450	14	0.8	134.4	3.8	43.7	1.23
2/3	9	.375	1.0	450	32	.445	171	2.6	64.1	0.99
Standard	14	.23	1.0	750	129	.403	624	6.2	143.5	1.43
Full	17	.07	1.0	900	238	.383	1094	8.9	76.6	0.63
Flank	17	0	1.0	900	128	.383	1094	8.9	0	0
Totals	-	1.0	-	-	-	-	-	-	327.9	4.28

TABLE 6-15b. OPTIMIZED FUEL CONSUMPTION -- WHEC PROPULSION SYSTEMS INC. PROPELLER

Mode	Ship Speed (Knots)	Modal Weight Factor	(P/D) Pitch Ratio	Engine RPM	BHP/cyl	lb/BHP-hr	Fuel Consumption		Weighted Fuel Consumption	
							lb/hr/eng	gal/mi/eng	lb/hr/eng	gal/mi/eng
Idle	0	0	0	450	0	-	-	-	0	0
1/3	5	.325	.55	450	14	0.8	134.4	3.8	43.7	1.23
2/3	9	.375	1.0	450	32	.445	170.9	2.6	64.1	0.99
Standard	14	.23	1.4	565	120	.399	574.6	5.7	132.1	1.31
Full	17	.07	1.3	690	216	.393	1018.6	8.9	71.3	0.58
Flank	18.0	0	1.15	900	300	.378	1360.8	10.2	0	-
Totals	-	1.0	-	-	-	-	-	-	311.2	4.11
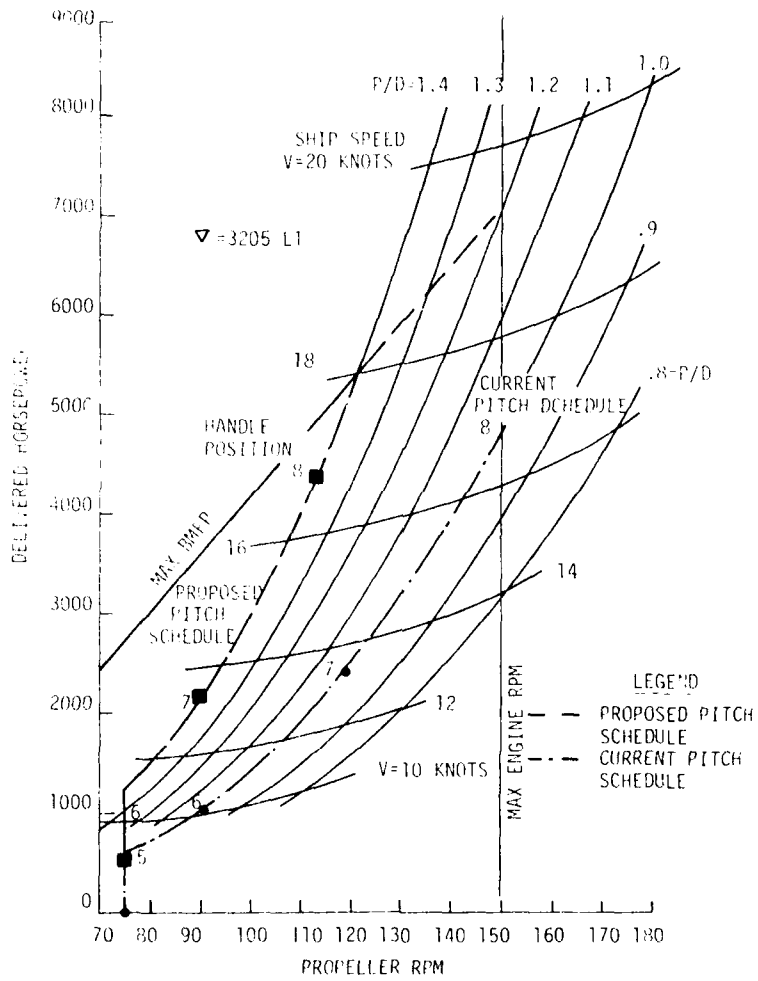
FIGURE 6-8. HYPOTHETICAL WHEC PITCH SCHEDULE, ESCHER-WYSS ® PROPELLER
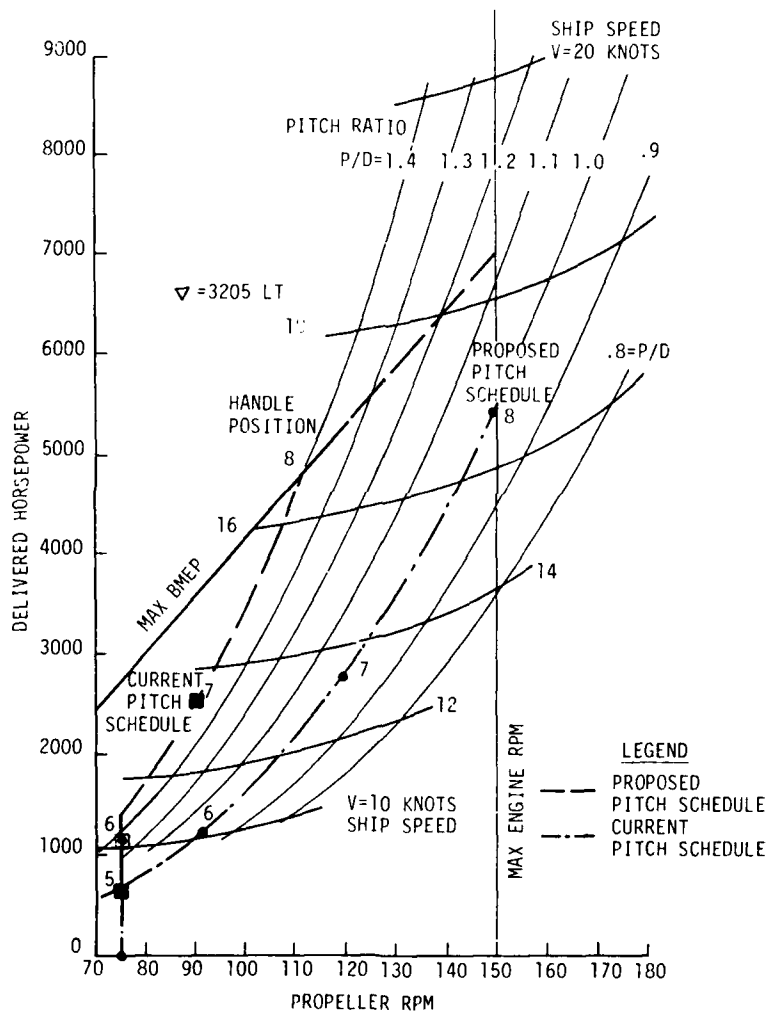
FIGURE 6-9. HYPOTHETICAL WHEC PITCH SCHEDULE, PROPULSION SYSTEMS, INC., ® PROPELLER
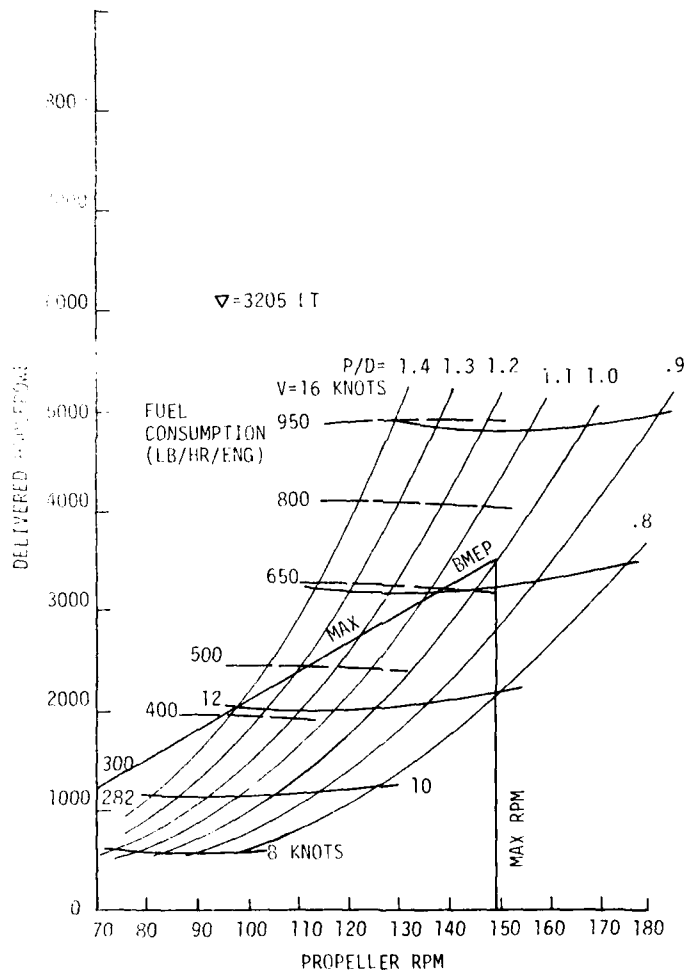
FIGURE 6-10. WHEC SINGLE ENGINE OPERATION, ESCHER-WYSS ® TRAIL SHAFT
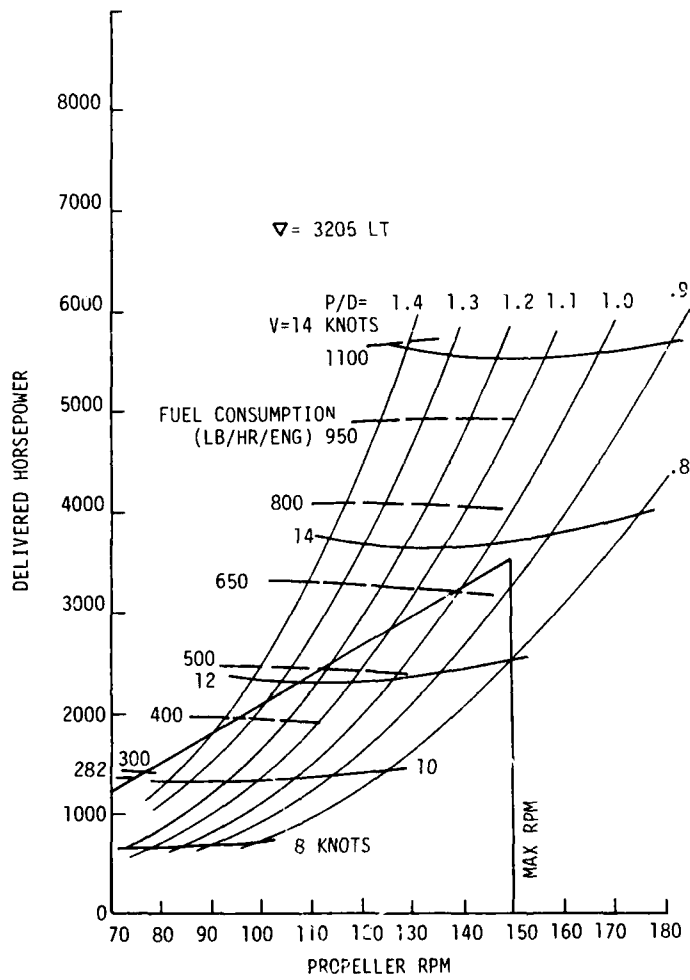
FIGURE 6-11.   WHEC SINGLE ENGINE OPERATION, PROPULSION SYSTEMS, INC., ®
TRAIL SHAFT

6-27
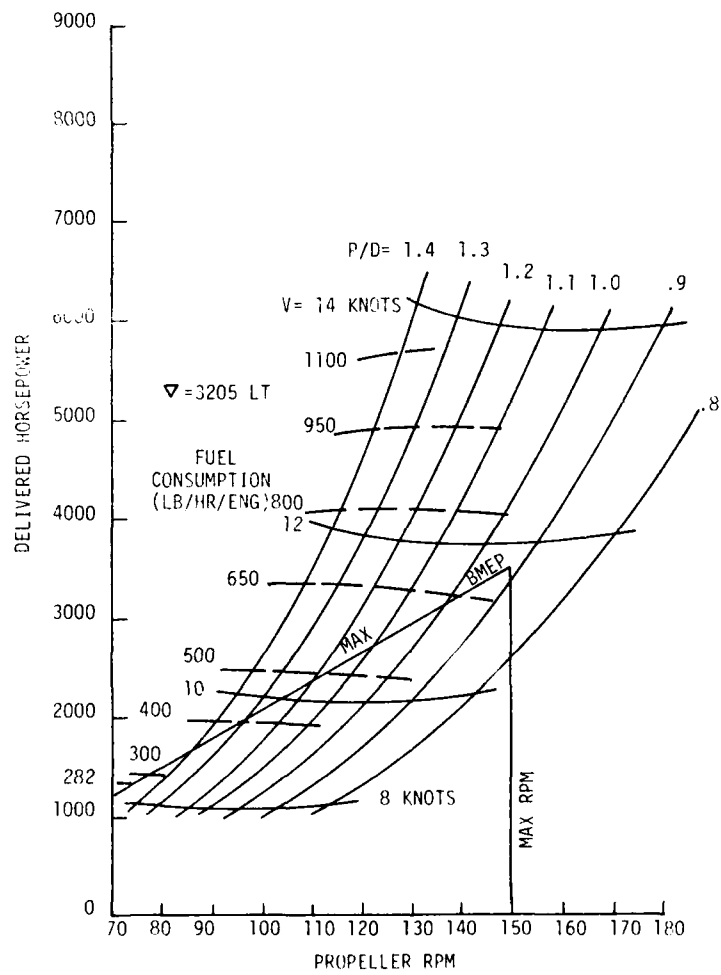
FIGURE 6-12. WHEC SINGLE ENGINE OPERATION, ESCHER-WYSS ® LOCKED SHAFT
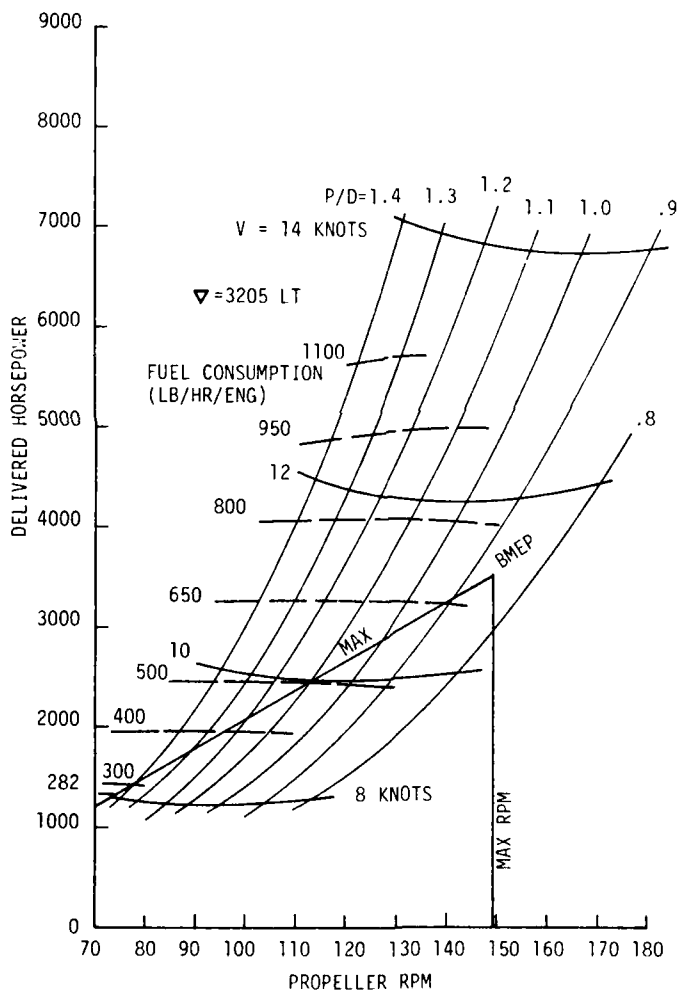
FIGURE 6-13. WHEC SINGLE ENGINE OPERATION, PROPULSION SYSTEMS, INC., ® LOCKED SHAFT
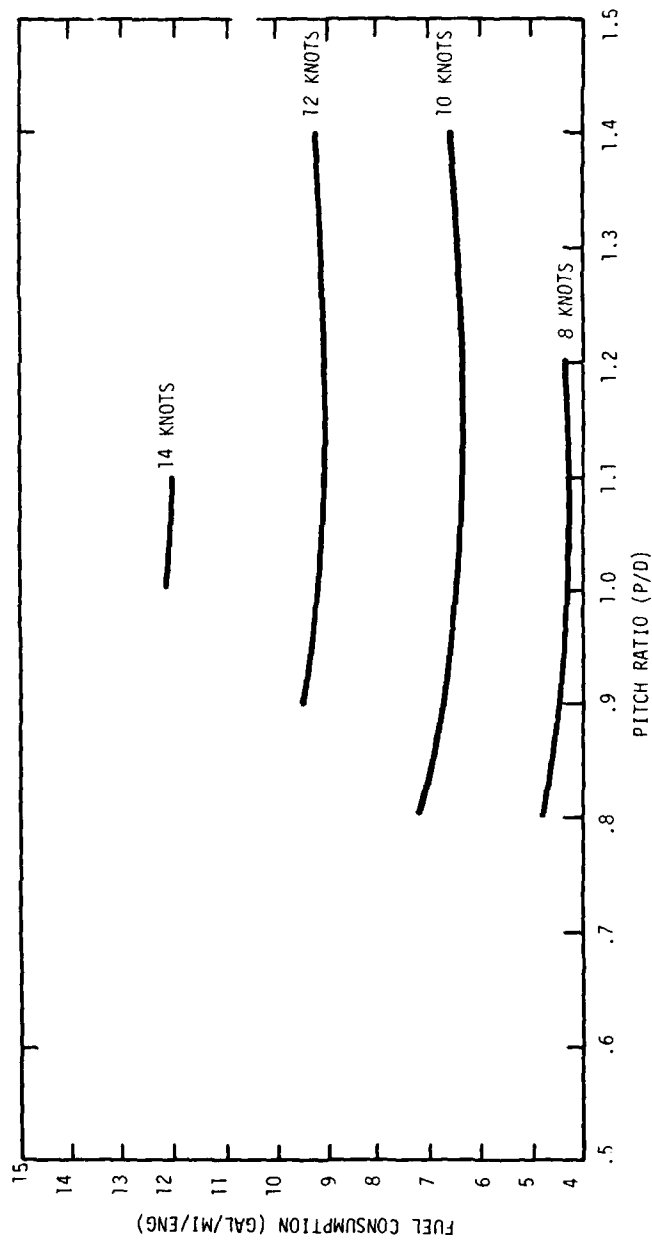
FIGURE 6-14. WHEC FUEL VOLUME FLOW RATE -- SINGLE ENGINE OPERATION, ESCHER-WYSS ® PROPELLERS TRAIL SHAFT
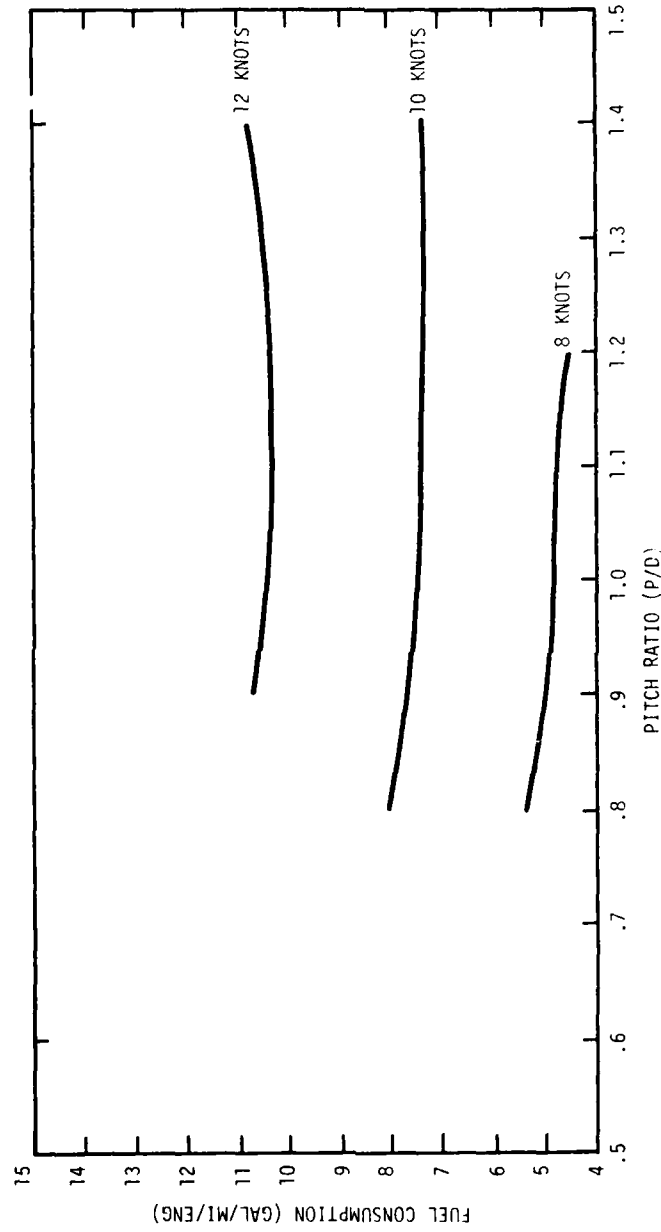
FIGURE 6-15. WHEC FUEL VOLUME FLOW RATE -- SINGLE ENGINE OPERATION, PROPULSION SYSTEMS, INC., ® PROPELLERS, TRAIL SHAFT

6-31
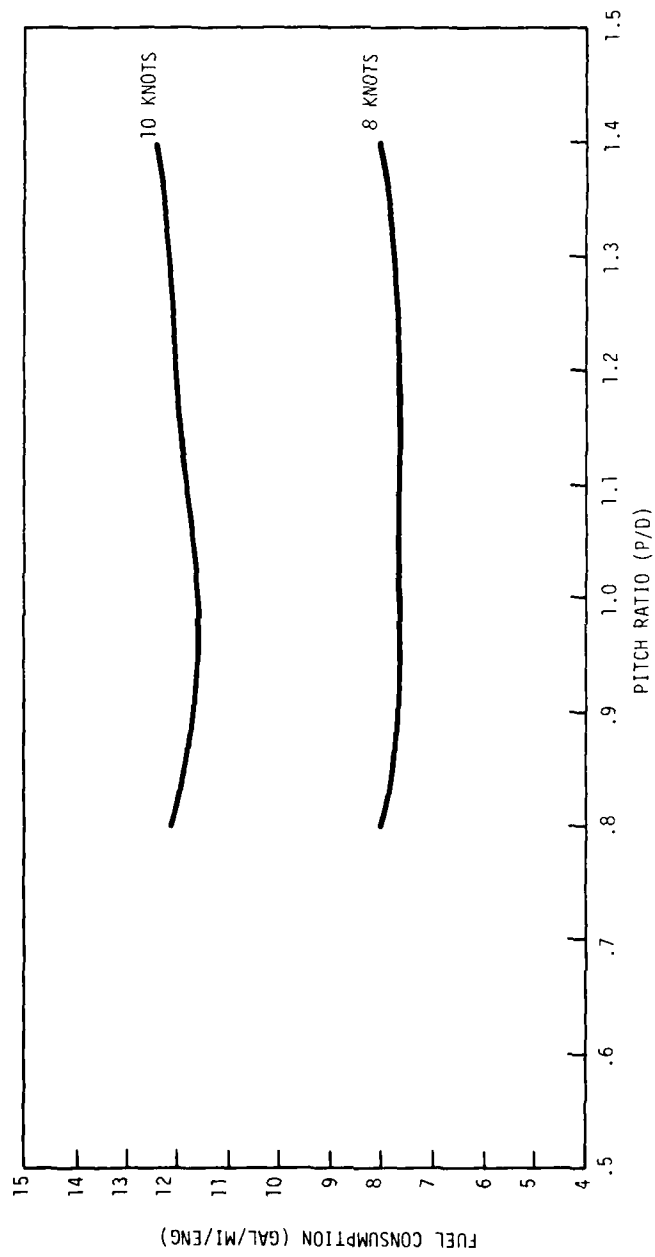
FIGURE 6-16. WHEC FUEL VOLUME FLOW RATE -- SINGLE ENGINE OPERATION, ESCHER-WYSS ® PROPELLERS, LOCKED SHAFT
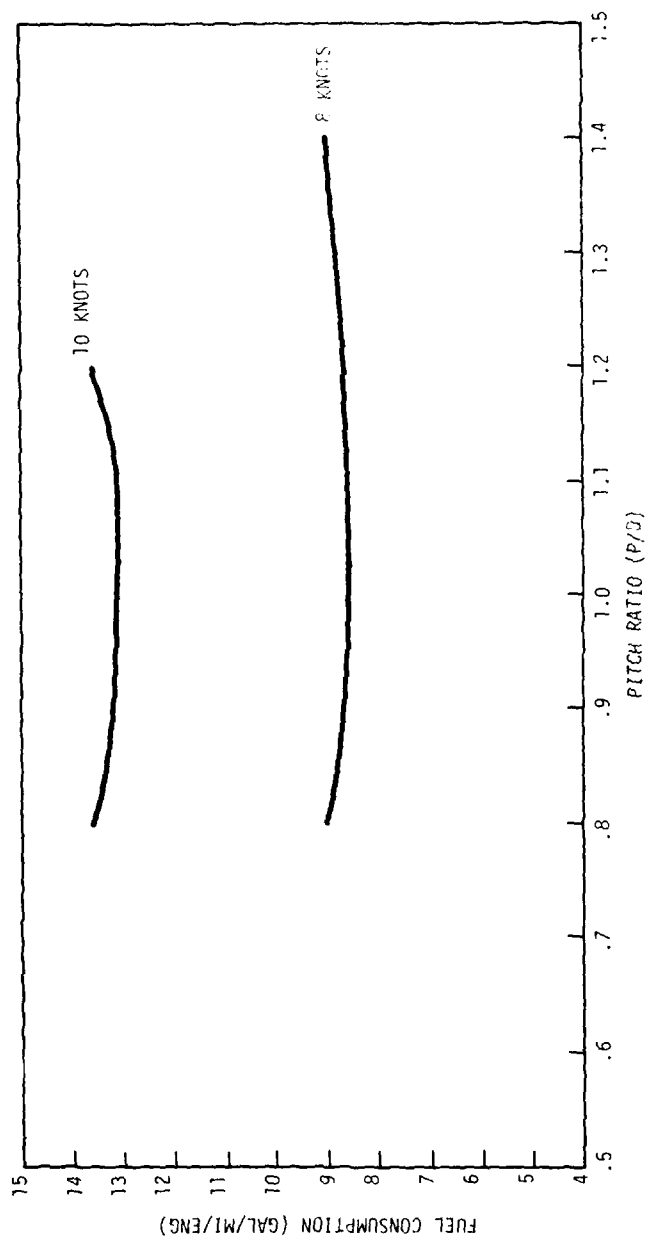
FIGURE 6-17. WHEC FUEL VOLUME FLOW RATE -- SINGLE ENGINE OPERATION, PROPULSION SYSTEMS, INC., ® PROPELLERS, LOCKED

Table 6-16 contains the optimum fuel consumption figures for various one- and two-engine configurations. In all cases, total fuel consumption for single-engine operation was greater than for two-engine operation at the same ship speed. However, data were not available for ship speeds below 10 knots. It is in this range that slow engine speed/low load conditions while operating on two engines could be transferred to higher speed/higher load combinations for a single engine, thus reducing brake specific fuel consumption and, possibly, reducing total fuel consumption. The data for this region could be obtained by expanding the low ship speed portion of the propeller diagram and the low speed/low load region of the engine performance map. This however, would require extensive additional analysis that was beyond the scope of this program.

The single-engine propeller diagrams verify Coast Guard observations that WHEC's can attain a speed of 10.5 knots at an engine speed of 660 RPM (109 propeller shaft RPM); standard practice is to use two engines above 10.5 knots.[7] The preferred type of operation would be with the free shaft rotating at maximum pitch since a locked shaft results in a large increase in drag and fuel consumption. (Therefore, provisions should be made to start the free propeller rotating in the event that it should stop.) The propeller diagrams and fuel consumption figures also reflect previous observations that the Escher-Wyss is the more efficient of the two propellers presently employed on the WHEC's.

TABLE 6-16.   378-FOOT SINGLE PROPELLER OPERATION

Type of Operation	Ship Speed (Knots)	Escher-Wyss ® Propellers					Propulsion Systems Inc. ® Propellers				
		Pitch Ratio (P/d)	Shaft RPM	Engine RPM	Total Fuel Consumption (lb/hr)	(gal/mi)	Pitch Ratio (P/d)	Shaft RPM	Engine RPM	Total Fuel Consumption (lb/hr)	(gal/mi)
Present 2 propeller cond.	8	-	-	-	-	-	-	-	-	-	-
Optimum 2 propeller cond.	8	-	-	-	-	-	-	-	-	-	-
Single Prop - Trail Shaft	8	1.0	73.5	443	249	4.3	1.2	73	440	280	4.5
Single Prop - Locked Shaft	8	1.0	95.5	576	442	7.7	1.1	99.5	540	493	6.6
Present 2 propeller cond.	10	1.0	89.5	540	438	6.2	1.0	89	537	484	5.8
Optimum 2 propeller cond.	10	1.3	72	434	386	5.4	1.3	72	434	458	7.4
Single Prop - Trail Shaft	10	1.2	92	555	459	6.4	1.2	92	555	528	7.4
Single Prop - Locked Shaft	10	1.0	120	724	830	11.6	1.1	112.5	679	943	13.1
Present 2 propeller cond.	12	1.0	107	646	734	8.6	1.0	107	646	812	9.7
Optimum 2 propeller cond.	12	1.4	80.5	486	648	7.6	1.4	80.5	486	734	9.6
Single Prop - Trail Shaft	12	1.2	110.5	667	785	9.1	1.1	117.5	709	889	10.5
Single Prop - Locked Shaft	12	-	-	-	-	-	-	-	-	-	-
Present 2 propeller cond.	14	1.0	124	748	1120	11.2	1.0	124	748	1249	24.9
Optimum 2 propeller cond.	14	1.4	94	567	992	9.8	1.4	93.5	564	1138	11.4
Single Prop - Trail Shaft	14	1.1	136	821	1209	12.0	-	-	-	-	-
Single Prop - Locked Shaft	14	-	-	-	-	-	-	-	-	-	-
Present 2 propeller cond.	16	1.0	142	857	1616	14.0	1.0	142	857	1844	15.8
Optimum 2 propeller cond.	16	1.4	107	646	1461	12.8	1.4	107	646	1628	14.6
Single Prop - Trail Shaft	16	-	-	-	-	-	-	-	-	-	-
Single Prop - Locked Shaft	16	-	-	-	-	-	-	-	-	-	-

Note: ` indicates that the value of BSFC was extrapolated from the engine performance map.

APPENDIX A

WHEC PROPELLER DIAGRAM CORRECTIONS

PROPELLER DIAGRAMS FOR THE US COAST GUARD

378-FOOT HIGH-ENDURANCE CUTTER

for

Southwest Research Institute
San Antonio TX

by

W. S. Vorus

M. G. Parsons

Department of Naval Architecture and Marine Engineering
The University of Michigan
Ann Arbor MI

December 1978

The propeller diagrams requested by your purchase order no. 120337 are the attached Figures 1 and 2.

Figure 1 is for the ships equipped with the Escher-Wyss propellers, and Figure 2 is for the ships equipped with the Propulsion Systems, Inc. propellers, as indicated thereon. The figures reflect a ship full load displacement of 3025 LT, which is some 10% in excess of the displacement for which the two propellers were reportedly designed. The figures give <u>delivered</u> horsepower for diesel operation versus propeller RPM for values of propeller pitch ratio and ship speed. The delivered power, being the power at the propeller, should be around 97% of the power output at the reduction gear (SHP).

The procedure followed in constructing Figures 1 and 2 consisted of 3 parts:

1) Correction of the original EHP curve to allow for the overweight condition of the vessels.

2) Construction of the diagram for the Escher Wyss propellers.

3) Construction of the diagram for the PSI propellers.

Each of these parts is described in the following.

EHP CURVE

The original EHP test (TMB file 9021, dated June 1963) was conducted at an equi-valent ship displacement of 2716 tons, corresponding to a draft of 13.5 ft with zero trim.

The actual full load condition of the ships is reported to correspond to a dis-placement of 3025 tons with a draft at the center of flotation of 14.4 ft. The curves of form for the ships then imply a 6.3% increase in wetted-surface over the original design condition of 2716 tons.

Using the ITTC-1957 friction line with $\Delta C_f = .0004$, the viscous component of the resistance was increased over the speed range in proportion to the increase in wetted-surface; the residuary resistance component was left unchanged.

The resulting EHP curve is included herein on Figure 3a. Figure 3a shows both the original and the corrected trial condition EHP curves; the original EHP is increased on the order of 3% by the vessel overweight.

ESCHER WYSS ® PROPELLER DIAGRAM

The EW diagram, Figure 1, represents, in essence, a correction and expansion of the low speed (diesel) region of the existing diagram (USCG Dwg. 719WPG-4400-118). The following steps were taken:

1) The existing diagram was very simply used to back-out the open-water characteristics (K_t, K_q versus J) of the EW propeller in the speed range of interest.

2) The corrected EHP curve was used along with the K_t - J curve from 1) to determine the new RPM/speed relationship.

3) The delivered power was calculated for the equilibrium RPM determined in 2) using the K_q - J curve from 1).

PSI PROPELLER DIAGRAM

For this propeller the only available information considered to be reliable was the open-water curves at the design pitch ratio of 1.25 (PSI drawing no. 16055-B). A propeller diagram similar to that of the EW propeller was available, but obviously er-roneous. The available PSI diagrams imply a substantially higher propeller open-water efficiency at the design pitch ratio than PSI actually achieved. The open-water curve at the design P/D (dwg. no. 16055-B) shows an efficiency at the design condition of about 64%. This is quite low for propellers of these general characteristics; the
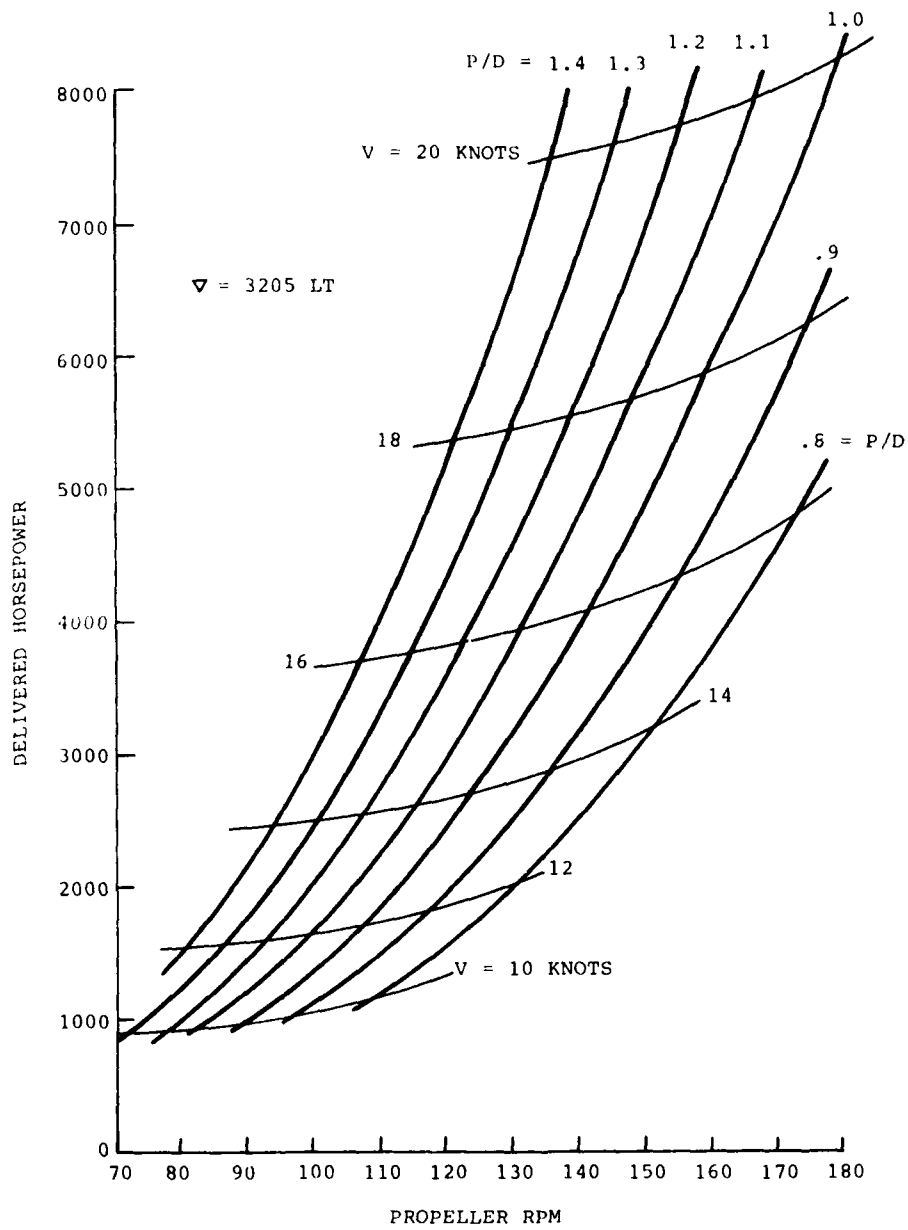
FIGURE A-1.   USCG 378-FOOT HEC ESCHER-WYSS ® PROPELLERS

A-4
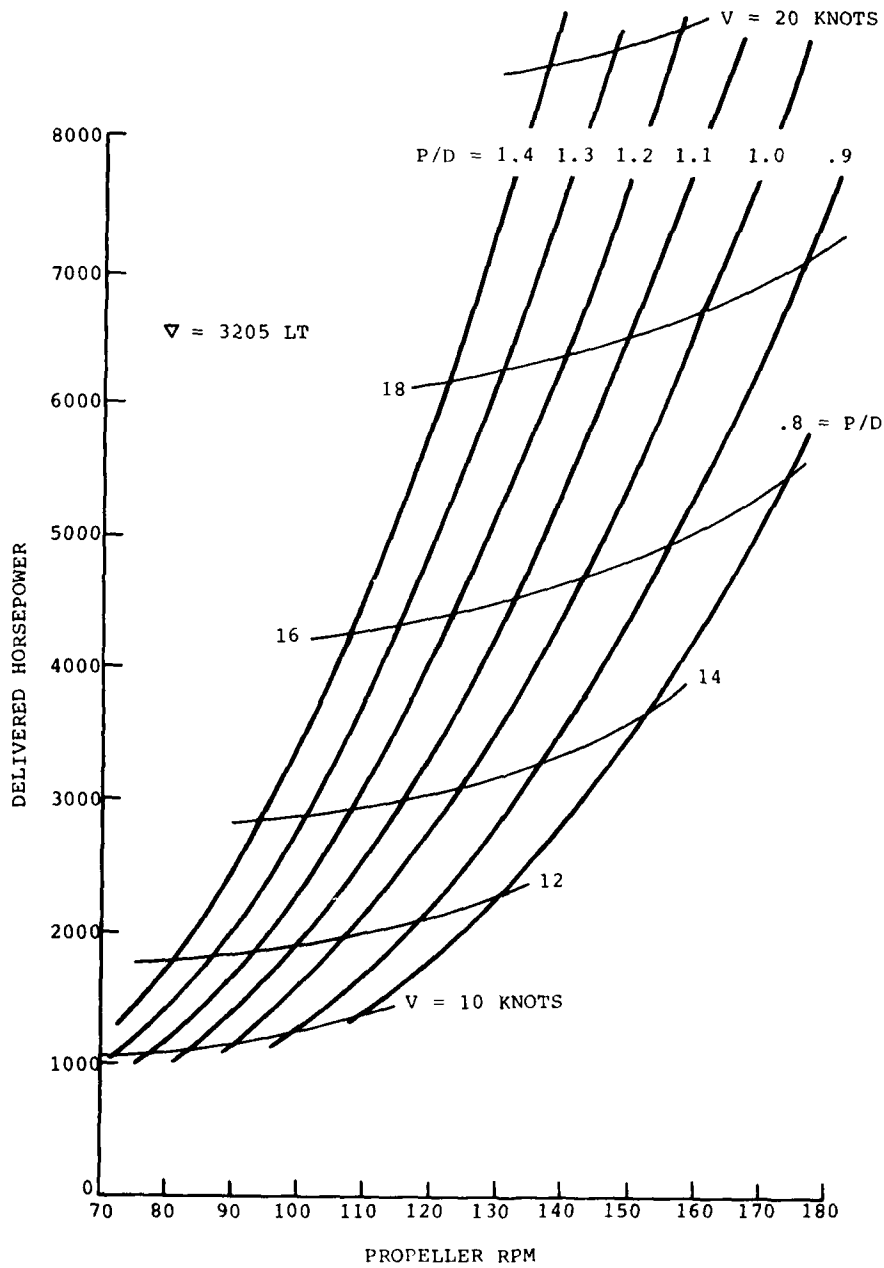
FIGURE A-2.   USCG 378-FOOT HEC PROPULSION SYSTEMS, INC., ® PROPELLERS

A-5
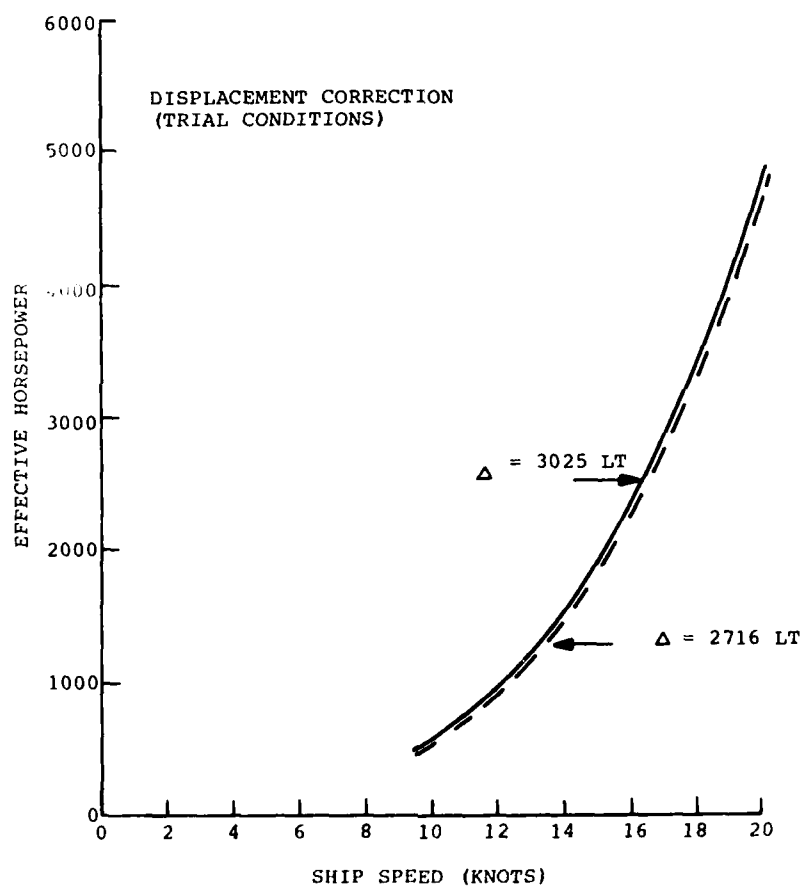
FIGURE A-3a. EHP VS. SPEED USCG 378-FOOT HEC

A-6

equivalent NSMB B4 series propeller has an open-water efficiency of 74%. A conjecture is that the diagrams might have been prepared with preliminary data based on a typically higher propeller efficiency and never corrected. The SHP curve from TMB file 9021, for example, implies a propeller efficiency in excess of 70%.

At any rate, the existing PSI diagram was deemed useless for the objectives of this work. The following steps were taken to produce Figure 2:

1) The K_t - J curve for the PSI propeller at the design P/D matches almost exactly that constructed, as described above, for the EW propeller at the same P/D. This would not be unexpected since the design RPM-speed-pitch characteristics of the 2 propellers are virtually identical. The K_t - J curves for the PSI propeller were therefore assumed to be the same as the K_t - J curves for the EW propeller at all pitch ratios of interest.

2) The efficiency difference between the PSI and EW propellers was known at the design P/D only (the maximum efficiency of the EW propeller at P/D = 1.25 was calculated to be 73% from the K_t, K_q, J curves constructed as described above). This maximum efficiency difference, percentage-wise, was assumed to be the same at all P/D. This established one point on the family of K_q - J curves for the PSI propeller. The values of J at K_q = 0 was then assumed to be the same for both propellers at corresponding pitch ratios. The two points then established the essentially linear K_q - J characteristics for the PSI propeller in the speed range of interest.

3) With the open-water characteristics of the PSI propeller in hand, the additional steps followed in constructing Figure 2 were identically the same as steps 2) and 3) for the EW propeller and Figure 1 as described above. Actually, with the same K_t - J curves the speed/RPM relationships from step 2) of the EW procedure apply for the PSI propeller; only step 3) of the EW procedure had actually to be executed to complete the data needed for the construction of Figure 2.

With regard to the accuracy of this work, it is expected that Figure 1 is as accurate as its input, and Figure 2 is within 2% of the accuracy of its input.

There appears to be no good reason to question the accuracy of the input data used, with one reservation: this involves the last paragraph on page 3 of the SWR Progress Report No. 9 to the USCG. This paragraph states the observation that the ships equipped with the Escher Wyss propeller turn slow; pitch must be reduced to P/D ≈ 1.1 to attain the design RMP at full power. To the contrary, Figure 1 shows that the EW propeller should achieve the design full power RPM at near the design P/D. It is the PSI propeller that this work would predict to turn slow at the design P/D. Figure 2, in fact, implies a pitch ratio of very near 1.1 at the full power and RPM. This is, of course, due to the low efficiency of the PSI propeller relative to that of the EW propeller, whose efficiency is not unusually high.

Again, a conjecture is that the statement on page 3 of the progress report has the EW and PSI propellers confused. Confirmation of this conjecture should remove all reservations regarding the reliability of Figures 1 and 2.

Author's Note: The conjecture in the final paragraph was found to be true, verifying the contents of this report.

PROPELLER DIAGRAMS FOR THE US COAST GUARD

378-FOOT HIGH ENDURANCE CUTTER; LOCKED AND

TRAIL SHAFT CONDITIONS

for

Southwest Research Institute
San Antonio TX

by

W. S. Vorus

M. G. Parsons

Department of Naval Architecture and Marine Engineering
The University of Michigan
Ann Arbor MI

September 1979

The work requested by your purchase order no. 146811 has been completed and is reported herein. This work is supplementary to that previously reported in reference 1. In reference 1 propeller diagrams were developed for the U.S. Coast Guard 378-foot High Endurance Cutters for diesel operation. As two different propellers are installed on different ships within the class, two propeller diagrams were delivered with reference 1: one for ships equipped with Escher Wyss propellers, and one for the ships equipped with Propulsion Systems, Inc. propellers.

The subject purchase order subsequently requested that additional propeller diagrams be developed for the same ships operating with one of the two main engines secured. However, two modes of operation on one engine are apparently possible for the subject ships: 1) a _locked_ shaft mode where the inoperable propeller is restrained from rotating by a shaft locking device, and 2) a _trail_ shaft mode where the inoperable system is allowed to rotate in response to hydrodynamic torque developed by the trailing propeller. In order to cover the two single engine operating modes on all ships, it was therefore necessary to develop four new propeller diagrams; these diagrams are Figures 3 through 6 of this report. Figures 3 and 5 are the trail and locked shaft diagrams for the Escher Wyss propellers and Figures 4 and 6 are the corresponding diagrams for the PSI propellers.

The effect of the trailing or locked propeller is to increase the apparent resistance of the hull as seen by the driving propeller. Therefore, in constructing Figures 3 through 6, the EPH data of reference 1 was first augmented by appropriate amounts to allow for the locked or trailing propeller. The propeller open-water curves developed in connection with reference 1 were then used as described therein, along with the augmented EHP data, to construct the new Figures 3 through 6.

The resistance augmentation of the inoperable propeller at any speed was taken as the negative propeller thrust developed at that speed. The CP propeller data presented in reference 2 was used for this purpose. In the locked shaft cases the thrust was taken as the zero RPM value corresponding to the ship speed of interest. For the trail shaft estimates an iteration was first performed in order to determine the RPM of the trailing propeller as a function of ship speed. This equilibrium RPM was estimated by balancing the propeller hydrodynamic torque against the friction torque developed in the rotating propulsion system. The system friction torque was taken as 14% of the steady ahead torque at any RPM on the basis of data contained in reference 3. The CP propeller data from reference 2, with a correction for efficiency differences, was used to estimate the propeller hydrodynamic torque. On determining the equilibrium RPM in the trailing condition at a selected speed, the negative thrust required was then extracted directly from reference 2.

The accuracy of the Figures 3b through 6 data is considered to be consistent with that presented on Figures 1, 2 and 3a of reference 1.

REFERENCES

1. "Propeller Diagrams for the US Coast Guard 378-Foot High Endurance Cutter," by W.S. Vorus and M.G. Parsons, dated December 1978.

2. Strom-Tejsen, J., and Porter, R.R., "Prediction of Controllable-Pitch Propeller Performance in Off-Design Conditions," Third Ship Control Symposium, Bath, UK, 1972.

3. "Marine Diesel Power Plant Performance Practices," SNAME T&R Bulletin #3-27, 1973.
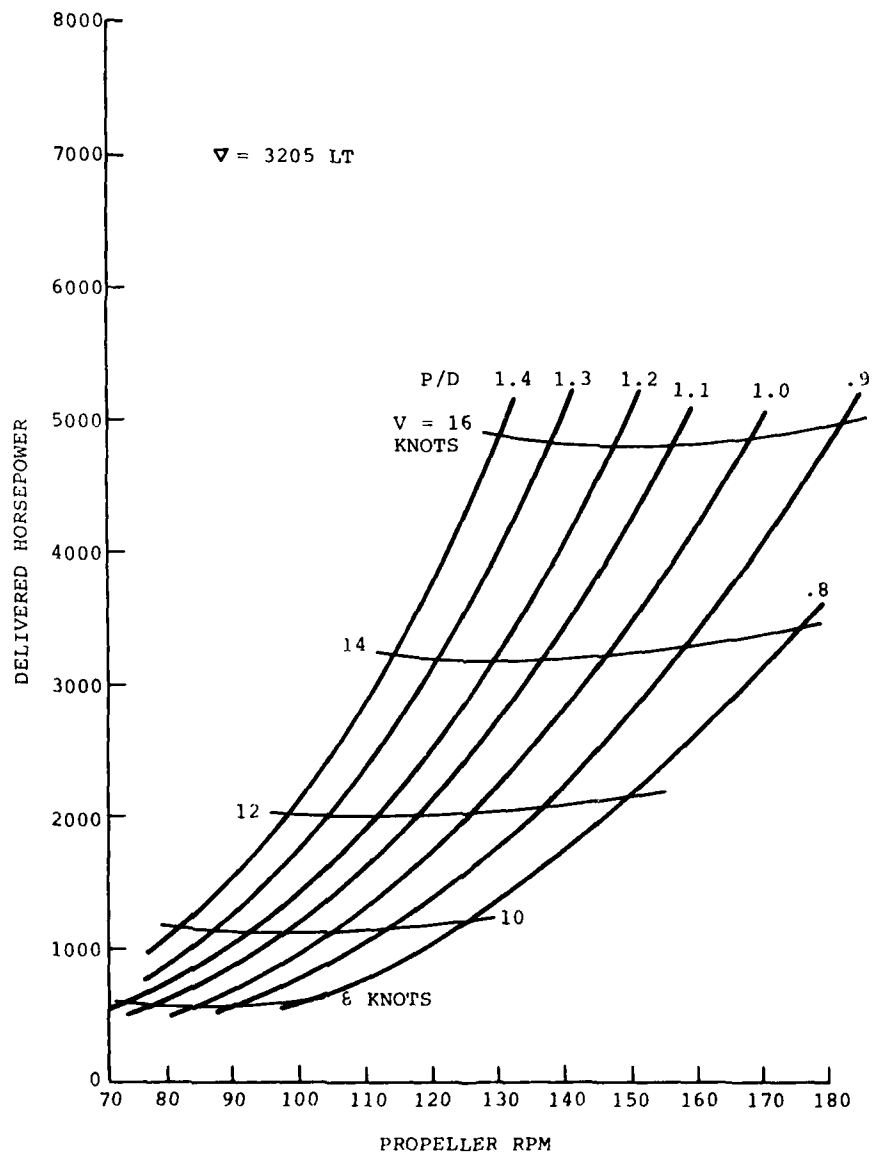
FIGURE A-3b. USCG 378-FOOT HEC ESCHER-WYSS ® PROPELLERS TRAIL SHAFT
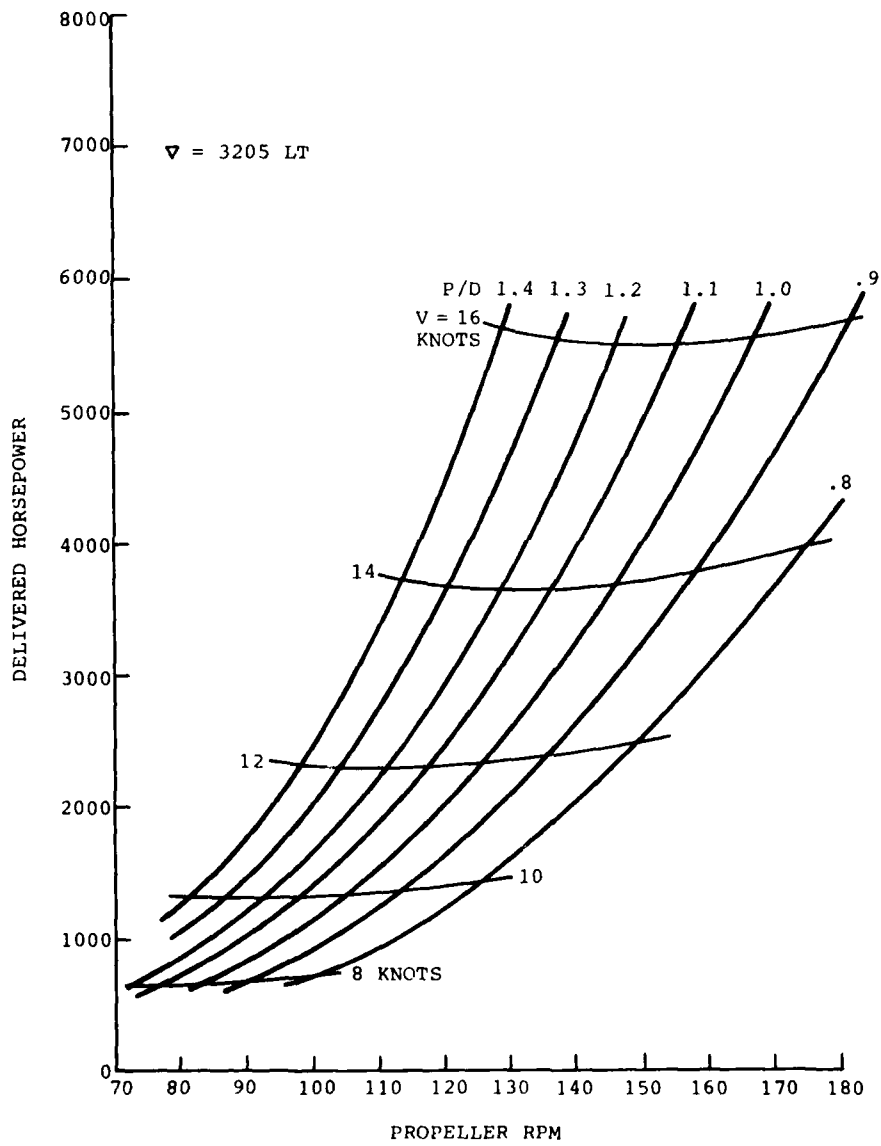
FIGURE A-4. USCG 378-FOOT HEC PROPULSION SYSTEMS, INC., ® PROPELLERS TRAIL SHAFT

A-11
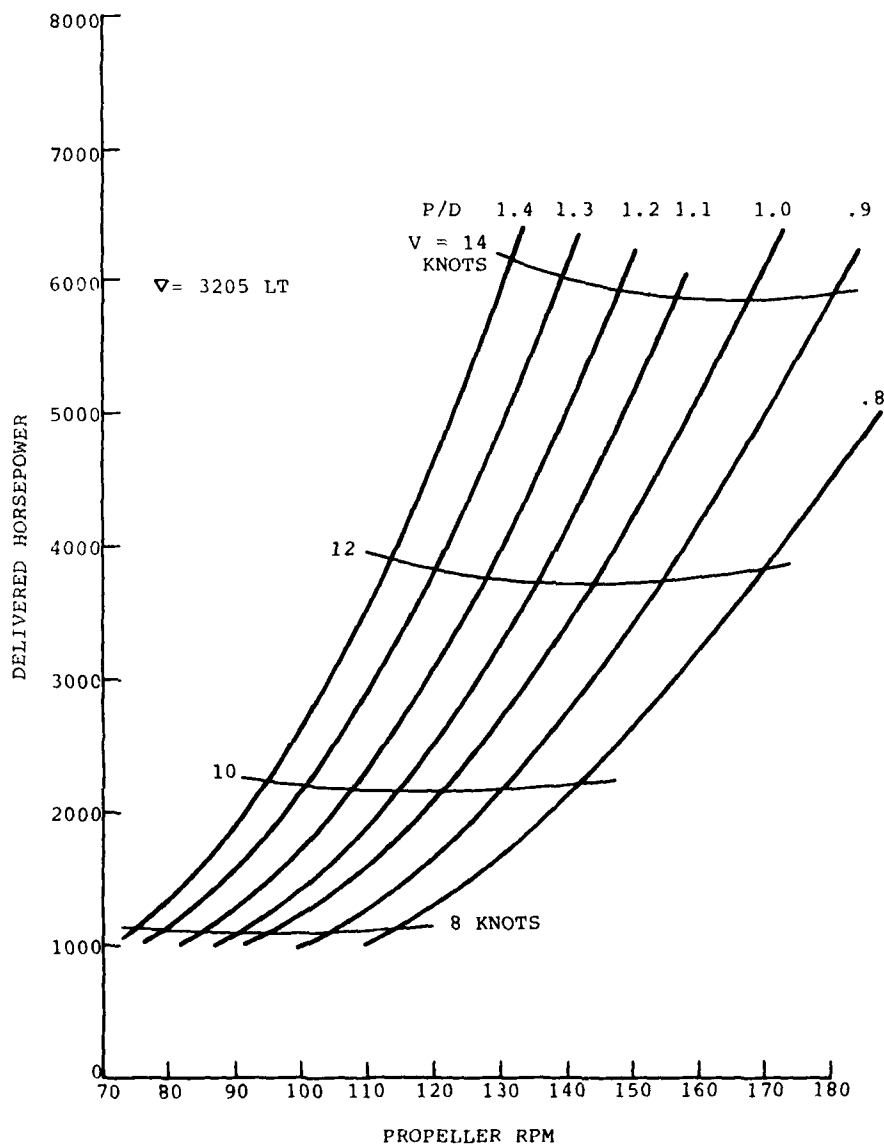
FIGURE A-5. USCG 378-FOOT HEC ESCHER-WYSS ® PROPELLERS LOCKED SHAFT
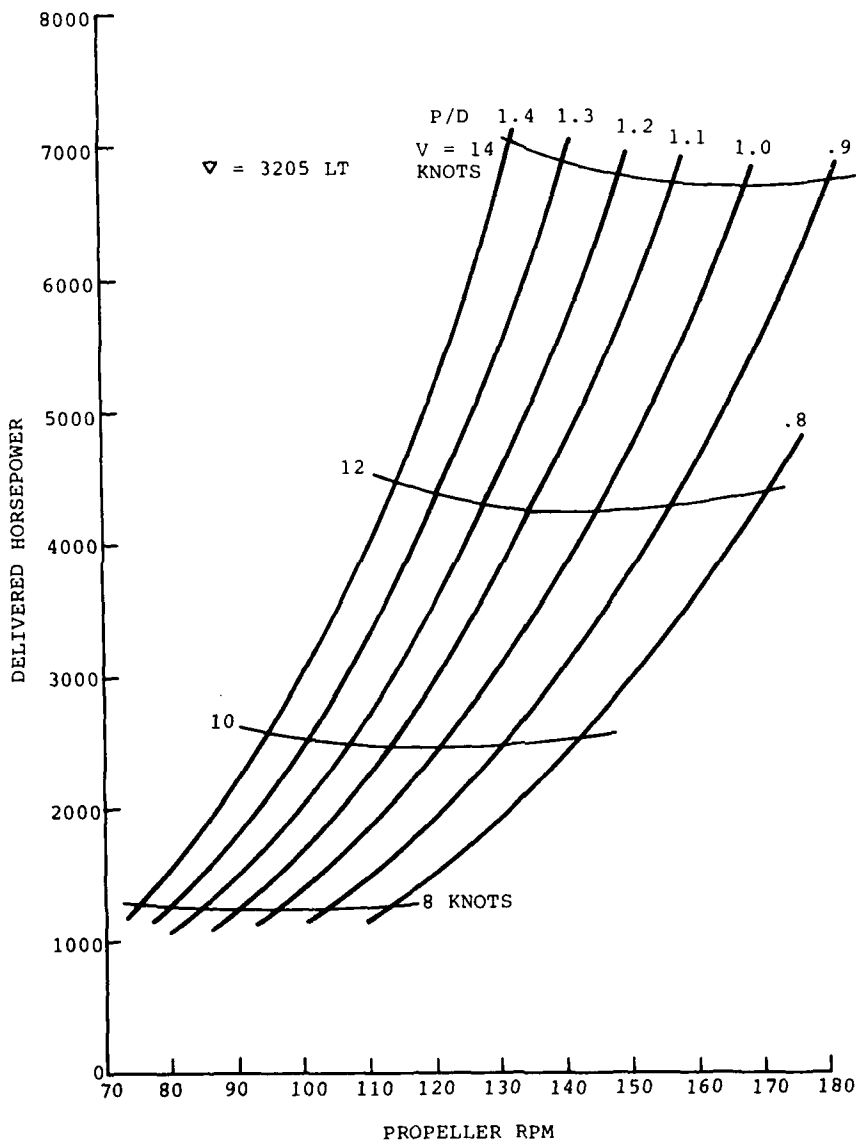
FIGURE A-6.   USCG 378-FOOT HEC PROPULSION SYSTEMS, INC., ® PROPELLERS LOCKED SHAFT

APPENDIX B

FUEL CONSUMPTION CALCULATIONS FOR WHEC AND WMEC

378-FOOT WHEC MAIN DIESEL ENGINE FUEL CONSUMPTION DATA, PSI PROPELLER, NORMAL 2 PROPELLER OPERATION

Ship Speed, Knots	SHP	SRPM	ERPM	BHP/Cyl.	BSFC	Fuel Consumption		% Incr. from Lowest value
						Lbm/hr/eng.	gal/mi/eng.	
P.R.= 1.4								
10	-	-	-	-	-	-	-	-
12	1775	80.5	486	74.0	.412	367	4.3	0
14	2850	93.5	564	118.8	.399	569	5.7	0
16	4275	107	646	178	.395	844	7.3	0
18	6200	121.5	733	258	-	-	-	-
20	8550	136	821	356	-	-	-	-
P.R.= 1.3								
10	1050	72	434	44	>.420	>.222	>3.1	0
12	1800	86	519	75	.414	373	4.3	0
14	2900	101	609	121	.399	579	5.8	1.7
16	4350	114.5	691	181	.392	851	7.4	1.4
18	6275	129.5	781	261	.386	1209	9.4	0
20	8700	145.5	878	363	-	-	-	-
P.R.= 1.2								
10	1075	77.5	468	45	>.420	>227	>3.2	
12	1850	92.5	558	77	.415	383	4.5	4.7
14	2950	107.5	649	123	.400	590	5.9	3.4
16	4425	123	742	184	.389	859	7.5	2.7
18	6375	139.5	842	266	.381	1216	9.4	0
20	8875	155.5	938	370	-	-	-	-
P.R.= 1.1								
10	1100	82.5	498	46	>.420	>232	>3.2	
12	1900	99.5	600	79	.416	394	4.6	7.0
14	3000	115	694	125	.401	602	6.0	5.3
16	4525	131	790	189	.389	882	7.7	5.5
18	6525	148.5	896	271	.380	1236	9.6	2 1
20	-	-	-	-	-	-	-	-
P.R.= 1.0								
10	1150	89	537	48	>.420	>242	>3.4	
12	1950	107	646	81	.418	406	4.7	9.3
14	3100	124	748	129	.403	624	6.2	8.8
16	4700	142	857	196	.388	913	7.9	8.2
18	6775	160.5	968	282	-	-	-	-
20	-	-	-	-	-	-	-	-
P.R.= 0.9								
10	1200	97.5	588	50	>.420	>252	>3.5	
12	2075	117	706	86	>.420	433	5.0	16.3
14	3300	136	821	138	.404	669	6.7	17.5
16	4950	155.5	938	206	-	-	-	-
18	7150	175	1056	298	-	-	-	-
20	-	-	-	-	-	-	-	-
P.R.= 0.8	1350	109	658	56	>.420	>282	>3.9	
12	2300	130	784	96	>.420	>484	>5.6	
14	3675	151.5	914	153	-	-	-	-
16	5525	173.5	1047	230	-	-	-	-
18	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-

Note: > indicates values which were approximated.

WHEC CONSTANT FUEL CONSUMPTION DATA - MAIN DIESEL ENGINE

Fuel Cons. lb/hr/eng.	BSFC lb/Bhp-hr	Bhp/Cyl.	ERPM	SRPM	Shaft Hp. (2 shafts)
282	.420	56	400	66	1344
282	.420	56	440	73	1344
300	.420	59.5	480	79.5	1429
300	.420	59.5	375	62.1	1429
400	.42	79.4	650	108	1906
400	.41	81.3	440	73	1951
400	.41	81.3	530	88	1951
500	.42	99.2	770	128	2381
500	.41	101.6	405	67	2439
500	.41	101.6	685	114	2439
650	.41	137.1	435	72	3171
650	.41	137.1	865	143	3171
650	.40	135.4	500	83	3250
650	.40	135.4	740	123	3250
650	.399	135.8	585	97	3259
650	.399	135.8	640	106	3259
800	.399	167.1	895	148	4010
800	.399	167.1	590	98	4010
800	.400	167	543	88	4000
800	.395	168.8	650	108	4051
800	.395	168.8	860	143	4051
950	.399	198.4	620	103	4762
950	.395	200.4	660	109	4810
950	.390	203	710	118	4872
950	.387	204.6	770	128	4910
950	.387	204.6	875	145	4910
1100	.390	235	735	122	5641
1100	.387	237	760	126	5685
1100	.385	238	800	133	5714

MAIN DIESEL ENGINE FUEL CONSUMPTION DATA--WMEC 210B

Fuel Cons. lb/hr/eng.	bsfc lb/Bhp-hr.	Engine BHP/cyl.	ERPM	SRPM	Shaft Hp
150	.40	23.4	650	195	375
350	.40	54.7	975	293	875
	.365	59.9	455	137	959
	.365	59.9	815	245	959
550	.365	94.2	515	155	1507
	.355	96.8	605	182	1549
	.355	96.8	985	296	1549
	.350	98.2	825	243	1571
750	.355	132.0	655	197	2113
	.350	133.9	712	214	2143
	.348	134.7	755	227	2155
	.345	135.9	880	264	2174
950	.348	170.6	820	246	2730
	.345	172.1	885	266	2754
	.340	174.6	945	284	2794
1150	.335	214.6	1030	309	3433

CONSTANT FUEL CONSUMPTION DATA – SINGLE MAIN DIESEL ENGINE

Ship Speed Knots	SHP	SRPM	ERPM	Fuel Cons., lbm/hr/eng.	% Increase from Lowest Value	Fuel Cons., gal/mi/eng.	% Increase from lowest value
P.R. = 1.30							
12	358	157	523	141.4	0.6	1.6	-
13	477	171	570	183.6	-	2.0	-
14	650	187	623	240.5	-	2.4	-
15	840	204	680	305.8	-	2.8	-
16	1068	220	733	382.3	-	3.3	-
17	1410	239	797	497.7	-	4.1	-
18	2033	265	883	701.4	-	5.4	-
18.6	2260	272	907	775.2	-	5.8	-
P.R. = 1.20							
12	356	166	553	140.6	-	1.6	-
13	477	181	603	183.6	-	2.0	-
14	652	199	663	243.2	1.1	2.4	-
15	838	216	720	305.9	-	2.8	-
16	1068	232	773	384.5	0.6	3.3	-
17	1408	251	837	498.4	0.1	4.1	-
18	2035	277	923	702.1	0.1	5.4	-
18.5	2425	291	970	824.5	6.4	6.2	6.9
P.R. = 1.10							
12	360	177	590	142.2	1.1	1.6	-
13	483	193	643	186.9	1.8	2.0	-
14	660	213	710	249.5	3.7	2.5	4.2
15	840	231	770	309.1	1.1	2.9	3.6
16	1072	248	827	389.1	1.8	3.4	3.0
17	1413	269	897	501.6	0.8	4.1	-
18	2042	297	990	702.4	0.1	5.4	-
18.1	2120	300	1000	727.2	3.7	5.6	3.7
P.R. = 1.00							
12	370	191	637	148.0	5.3	1.7	6.2
13	492	207	690	195.3	6.4	2.1	5.0
14	670	228	760	256.6	6.7	2.5	4.2
15	850	246	820	318.8	4.2	3.0	7.1
16	1083	266	887	395.3	3.4	3.4	3.0
17	1430	290	967	511.9	2.8	4.2	2.4
17.2	1615	300	1000	571.7	14.9	4.6	12.2
P.R. = 0.90							
12	382	208	693	154.7	10.0	1.8	12.5
13	510	226	753	204.0	11.1	2.2	10.0
14	687	246	820	267.9	11.4	2.7	12.5
15	870	265	883	333.2	9.0	3.1	10.7
16	1110	286	953	412.9	8.0	3.6	9.1
16.5	1285	300	1000	471.6	23.4	4.0	21.2
P.R. = 0.80							
12	400	227	757	168.0	19.5	1.9	18.8
13	535	247	823	218.3	18.9	2.3	15.0
14	727	272	907	290.8	20.9	2.9	20.8
15	917	293	977	362.2	18.4	3.4	21.4
15.3	987	300	1000	386.9	26.5	3.5	25.0
P.R. = 0.70							
12	435	251	837	187.0	33.0	2.2	37.5
13	575	272	907	243.2	32.5	2.6	30.0
14	785	300	1000	327.3	36.1	3.2	33.3
P.R. = 0.60							
12	505	289	963	224.7	59.8	2.6	62.5
12.4	568	300	1000	249.9	77.7	2.8	75.0

378-FOOT WHEC MAIN DIESEL ENGINE FUEL CONSUMPTION DATA

Ship Speed, Knots	SHP (2 Shafts)	SRPM	ERPM	Engine BHP/cyl	BSFC lb/Bhp-hr	Fuel Consumption		% Incr. from Lowest Value
						lb/hr/eng	gal/mi/eng	
P.R.= 1.40								
10	-	-	-	-	-	-	-	-
12	1550	80.5	486	64.6	.418	324	3.8	0
14	2460	94	567	102.5	.403	496	4.9	0
16	3700	107	646	154	.396	732	6.4	0
18	5375	121.5	733	224	.389	1046	8.1	0
20	7475	135.5	818	312	-	-	-	-
P.R.= 1.3								
10	875	72	424	36.5	>.420	>184	>2.6	0
12	1575	86.5	521	65.5	.420	331	3.8	0
14	2500	100.5	606	104.2	.405	506	5.0	2.0
16	3775	114.5	691	157	.394	742	6.5	1.6
18	5475	129.5	781	228	.386	1056	8.2	1.2
20	7600	145	875	317	-	-	-	-
P.R.= 1.2								
10	900	77.5	468	38	>.420	>192	>72.7	+
12	1600	92.5	558	67	.420	338	3.9	2.6
14	2550	107.5	649	106	.406	516	5.1	4.1
16	3850	123	742	160	.393	755	6.6	3.1
18	5575	139	839	232	.384	1069	8.3	2.4
20	7725	155.5	938	322	-	-	-	-
P.R.= 1.1								
10	950	82.5	498	40	>.420	> 202	> 2.8	+
12	1650	99.5	600	69	>.423	> 350	>4.1	7.9
14	2625	115.5	697	109	.408	547	5.4	10.2
16	3950	131.5	793	165	.393	778	6.8	6.2
18	5725	148.5	896	239	.383	1098	8.5	4.9
20	7950	166.5	1004	331	-	-	-	-
P.R.= 1.0								
10	975	89.5	540	41	>.420	> 206	> 2.9	+
12	1725	107	646	72	>.420	> 363	>4.2	>10.5
14	2725	124	748	114	.409	560	5.6	14.3
16	4100	142	857	171	.394	808	7.0	9.4
18	5925	160.5	968	247	-	-	-	-
20	8275	180.5	1089	345	-	-	-	-
P.R.= 0.9								
10	1050	98	591	44	>.420	>221.8	>3.1	+
12	1825	117.5	709	76	>.420	>384	>4.5	>18.4
14	2900	136	821	121	.412	598.8	>6.0	>22
16	4450	155	935	185	-	-	-	-
18	6275	175	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-
P.R.= 0.8								
10	1150	109	658	48	>.420	>242	>3.4	+
12	2000	130	784	83	>.420	>419	>4.9	>29
14	3225	152	917	134	-	-	-	-
16	4800	173	1044	200	-	-	-	-
18	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-

Note: > indicates values which were approximated.

APPENDIX C

WHEC SINGLE PROPELLER OPERATION FUEL CONSUMPTION DATA

FUEL CONSUMPTION DATA

Escher Wyss Propeller - Trail Shaft

Knots	Pitch	Shaft Horsepower	Shaft RPM	Engine RPM	Bhp/cyl	BSFC (lb/Bhp-hr)	Fuel Consumption (lb/hr/eng)	(gal/mt/eng)	Δ % from Lowest Value (Volume Rate)
10	1.4	1160	81.5	492	96.7	.405	470	6.6	3.1
12	1.4	2025	97.5	589	169	.397	805	9.3	2.2
14	1.4	3225	113.5	685	269	-	-	-	-
16	1.4	4875	129.5	781	406	-	-	-	-
10	1.3	1140	86.5	522	95	.405	462	6.4	0
12	1.3	2000	97.5	588	167	.397	796	9.2	1.1
14	1.3	3200	113.5	685	267	-	-	-	-
16	1.3	4825	137.5	830	403	-	-	-	-
8	1.2	600	73.5	443	50	~.425	~255	~4.4	~2.3
10	1.2	1125	92	555	94	.407	459	6.4	0
12	1.2	1990	110.5	667	166	.394	785	9.1	0
14	1.2	3160	128	772	263	-	-	-	-
16	1.2	4800	147	887	400	-	-	-	-
9	1.1	590	78	471	49	~.430	~253	~4.4	~2.3
10	1.1	1125	97.5	588	94	.408	460	6.4	0
12	1.1	2000	117.5	709	167	.392	786	9.1	0
14	1.1	3160	136	821	263	.383	1209	12.0	0
16	1.1	4775	156	941	398	-	-	-	-
8	1.0	575	73.5	443	48	~.432	~249	~4.3	0
10	1.0	1150	105	634	96	.409	471	6.6	3.1
12	1.0	2025	125.5	757	169	.392	795	9.2	1.1
14	1.0	3200	146.5	884	267	.380	1218	12.1	0.1
16	1.0	4825	167.5	1011	669	-	-	-	-
8	0.9	590	91	550	49	~.438	~258	~4.5	4.7
10	0.9	1175	113.5	685	98	.413	486	6.8	6.3
12	0.9	2075	136.5	824	173	.393	816	9.5	8.2
14	0.9	3275	159	959	273	-	-	-	-
16	0.9	4950	181.5	1095	413	-	-	-	-
8	0.8	625	100	603	52	~.440	~275	~4.8	11.6
10	0.8	1225	126	760	102	.417	510	7.11	10.9
12	0.8	2175	150.5	908	181	-	-	-	-
14	0.8	3425	175	1056	285	-	-	-	-

NOTE: ~ indicates that the BSFC value was extrapolated from the engine map.

C-2

FUEL CONSUMPTION DATA

USCG 378-Foot WHEC Single Propeller Operation

Propulsion Systems Inc. Propellers - Trail Shaft

Knots	Pitch	Shaft Horsepower	Shaft RPM	Engine RPM	Bhp/cyl	BSFC (lb/Bhp-hr)	Fuel Consumption (lb/hr/eng)	Fuel Consumption (gal/ml/eng)	Δ % from Lowest Value (Volume Rate)
10	1.4	1325	81.5	492	110	.401	529	7.4	0
12	1.4	2325	97.5	588	194	.400	931	10.8	4.9
14	1.4	3700	113.5	685	308	-	-	-	-
16	1.4	5600	129.5	781	467	-	-	-	-
10	1.3	1315	86.5	522	110	.400	528	7.4	0
12	1.3	2300	113.5	685	192	.395	910	10.6	2.9
14	1.3	3650	120	724	304	-	-	-	-
16	1.3	5525	138	833	460	-	-	-	-
8	1.2	650	73	440	51	~.425	~260	~4.5	0
10	1.2	1315	92	555	110	.400	528	7.4	0
12	1.2	2275	110	664	190	.394	898	10.4	1.0
14	1.2	3625	128.5	775	302	-	-	-	-
16	1.2	5500	147	887	458	-	-	-	-
8	1.1	650	78	471	54	~.425	~275	~4.8	6.7
10	1.1	1325	98	591	110	.401	529	7.4	0
12	1.1	2275	117.5	709	190	.390	889	10.3	0
14	1.1	3625	136.5	824	302	-	-	-	-
16	1.1	5475	156	941	456	-	-	-	-
8	1.0	660	83.5	504	55	~.427	~282	~4.9	8.9
10	1.0	1325	115	694	110	.408	539	7.5	1.4
12	1.0	2300	125.5	757	192	.388	894	10.4	1.0
14	1.0	3675	146	881	306	-	-	-	-
16	1.0	5575	167.5	1011	465	-	-	-	-
8	0.9	675	91	549	50	~.430	~289	~5.0	11.1
10	0.9	1350	114	688	113	.405	549	7.7	2.7
12	0.9	2375	136.5	824	198	.388	922	10.7	3.9
14	0.9	3775	159	959	315	-	-	-	-
16	0.9	5675	181.5	1095	473	-	-	-	-
8	0.8	725	100.5	606	60	~.432	~311	~5.4	20
10	0.8	1425	126	760	119	.408	582	8.1	9.5
12	0.8	2500	150.5	908	208	-	-	-	-
14	0.8	3950	175.5	1059	329	-	-	-	-

NOTE: ~ Indicates that the BSFC value was extrapolated from the engine map

C-3

FUEL CONSUMPTION DATA

USCG 378-Foot WHEC Single Propeller Operation

Escher Wyss Propeller - Locked Shaft

Knots	Pitch	Shaft Horsepower	Shaft RPM	Engine RPM	Bhp/cyl	BSFC (lb/Bhp-hr)	Fuel Consumption (lb/hr/eng)	Fuel Consumption (gal/mi/eng)	Δ % from Lowest Value (Volume Rate)
8	1.4	1125	75.5	456	94	.406	458	8.0	3.9
10	1.4	2225	94.5	570	185	.400	888	12.4	5.2
12	1.4	3900	113.5	685	325	-	-	-	-
14	1.4	6150	131.5	793	513	-	-	-	-
8	1.3	1100	79.5	480	92	.406	448	7.8	2.6
10	1.3	2200	100	603	183	.397	872	12.1	4.3
12	1.3	3825	120	724	319	-	-	-	-
14	1.3	6025	139.5	842	502	-	-	-	-
8	1.2	1090	85	513	91	.406	443	7.7	0
10	1.2	2175	106.5	643	181	.395	858	12.0	3.4
12	1.2	3750	127	766	313	-	-	-	-
14	1.2	5925	148	893	494	-	-	-	-
8	1.1	1075	89.5	540	90	.407	440	7.7	0
10	1.1	2150	113	682	179	.393	844	11.8	1.7
12	1.1	3725	135	815	310	-	-	-	-
14	1.1	5875	156.5	944	490	-	-	-	-
8	1.0	1075	-	576	90	.409	442	7.7	0
10	1.0	2125	12.	724	177	.391	830	11.6	0
12	1.0	3725	144	869	310	-	-	-	-
14	1.0	5875	167.5	1011	490	-	-	-	-
8	0.9	1075	103.5	525	90	.412	445	7.7	0
10	0.9	2150	129.5	781	179	.390	838	11.7	0.8
12	0.9	3750	155	935	313	-	-	-	-
14	0.9	5925	180	1086	494	-	-	-	-
8	0.8	1100	113	682	92	.415	458	8.0	3.9
10	0.8	2225	142.5	860	185	.392	870	12.1	4.3
12	0.8	3825	170.5	1029	319	-	-	-	-

FUEL CONSUMPTION DATA

USCG 378-Foot WHEC Single Propeller Operation

							Propulsion Systems Inc. Propellers - Locked Shaft			
								Fuel Consumption		Δ % from Lowest Value
Knots	Pitch	Shaft Horsepower	Shaft RPM	Engine RPM	Bhp/cyl	BSFC (lb/Bhp-hr)	(lb/hr/eng)	(gal/mi/eng)	(Volume Rate)
8	1.4	1275	75.5	456	106	.405	515	9.0	4.7
10	1.4	2575	94.5	570	215	–	–	–	–
12	1.4	4475	113.5	685	373	–	–	–	–
14	1.4	7025	131.5	793	585	–	–	–	–
8	1.3	1250	79.5	480	104	.403	503	8.8	2.3
10	1.3	2500	100.5	606	208	–	–	–	–
12	1.3	4375	120.0	724	365	–	–	–	–
14	1.3	6875	139	639	573	–	–	–	–
8	1.2	1250	84.5	510	104	.402	502	8.7	1.2
10	1.2	2475	106.5	643	206	.396	979	13.6	3.8
12	1.2	4275	127.5	769	356	–	–	–	–
14	1.2	6775	148	893	565	–	–	–	–
8	1.1	1225	89.5	540	102	.403	493	8.6	0
10	1.1	2400	112.5	679	200	.393	943	13.1	0
12	1.1	4225	135	815	352	–	–	–	–
14	1.1	6700	157	947	558	–	–	–	–
8	1.0	1225	95.5	576	102	.404	494	8.6	0
10	1.0	2450	120	724	204	.389	953	13.2	1.5
12	1.0	4225	144	869	352	–	–	–	–
14	1.0	5700	167	1008	558	–	–	–	–
8	0.9	5	103.5	624	102	.407	498	8.7	1.2
10	0.9		129	778	204	.387	947	13.2	0.8
12	0.9		155	935	358	–	–	–	–
14	0.9	6750	180.5	1089	563	–	–	–	–
8	0.8	1275	113.5	684	106	.408	519	9.0	4.7
10	0.8	2525	142	857	210	.386	973	13.6	3.8
12	0.8	4375	170.5	1029	365	–	–	–	–

APPENDIX D

REPORT OF NEW TECHNOLOGY

New operational techniques for improving the fuel consumption of the Coast Guard large cutters consisting of reprogramming pitch schedules to optimize fuel-consumption characteristics are discussed, and illustrated, on pages 6-16 to 6-35/6-36. These techniques offer fuel-economy improvements from 3 to 5 percent.

180 copies

DATE
ILMED
-8