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David Taylor Research Center
Bethesda, Maryland 20084-5000

DTRC/SHD-1312-03 April 1990

Ship Hydromechanics Department
Departmental Report

UNDERWAY REPLENISHMENT INVESTIGATION FOR SELECTED SURFACE SHIPS

by
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DTRC/SHD-1312-03 Underway Replenishment Investigation for Selected Surface Ships

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; Distribution is unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) DTRC/SHD-1312-03	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION David Taylor Research Center Ship Hydromechanics Dept. — 6b OFFICE SYMBOL (If applicable) Code 1561	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Bethesda, Maryland 20084-5000	7b ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING / SPONSORING ORGANIZATION Chief of Naval Research — 8b. OFFICE SYMBOL (If applicable) ONT 211	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Arlington, Virginia 22217-5000	10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
62121N	RH21S23	5	DN178067

11. TITLE (Include Security Classification)
UNDERWAY REPLENISHMENT INVESTIGATION FOR SELECTED SURFACE SHIPS

12. PERSONAL AUTHOR(S)
T.C. SMITH and W.L. THOMAS III

13a. TYPE OF REPORT	13b TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Final	FROM 11/90 TO 03/90	1990 April	23

16 SUPPLEMENTARY NOTATION
DTRC Work Unit No. 1-1506-020-21

17 COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Underway Replenishment, Criteria sets, Connected Replenishment, Vertical Replenishment, Fueling Along Side.

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

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20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Timothy C. Smith	22b TELEPHONE (Include Area Code) 202-227-5117 — 22c OFFICE SYMBOL Code 1561

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

S/N 0102-LF-014-6603

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NOMENCLATURE

CG	Center of Gravity
CONREP	Connected Replenishment
FAS	Fueling At Sea
L_{pp}	Length between perpendiculars
RAST	Recovery Assist Securing and Traverse System
SSA	Significant Single Amplitude
STREAM	Standard Tensioned Replenishment Alongside Method
UNREP	Underway Replenishment
VERTREP	Vertical Replenishment

ABSTRACT

This report applies Underway Replenishment criteria to a representative fleet of 16 Naval ships. Underway Replenishment of three types are examined, Connected Replenishment, Fueling At Sea, and Vertical Replenishment. The Percent Time Operabilities for each ship and mission are presented. The limiting response by ship and mission was also found.

ADMINISTRATIVE INFORMATION

This investigation was sponsored by the Chief of Naval Research, Office of Naval Technology, Code ONT211, under the 6.2 Surface Ship Technology Program (ND1A), Program Element 62121N, Advanced Hull Project RH21S23, Task 5, Ship Motion Control. The work was performed at the David Taylor Research Center during FY1990 under work unit number 1-1506-020. The DN number is DN178067.

INTRODUCTION

Throughout history, ships have been required to operate in adverse conditions including strong winds, precipitation, sub-freezing temperatures, and heavy seas. The environmental factor which affects seakeeping quality is the ocean waves. When sea conditions worsen, the operational capability of a ship decreases due to excessive motions. Degradations can range from mild cases of motion sickness to severe restrictions on equipment operability. In extreme cases, a ship's capability can be reduced to a point where survival becomes questionable.

Underway Replenishment (UNREP) describes the transfer of fuel, munitions, supplies, and personnel from one vessel to another while ships are at sea. The capability to conduct UNREP operations is very important because it allows ships to remain at sea for prolonged periods of time. The ability of the U. S. Navy to project seapower and conduct sustained operations in remote ocean regions is directly linked to its UNREP capability. Navies without UNREP capability must return to port when fuel or cargo supplies become depleted.

Underway Replenishment evolutions are manpower intensive and are particularly sensitive to degradation in heavy seas due to excessive ship motions. This seakeeping study was initiated to examine ship motion sensitivity as related to UNREP evolutions among a variety of Naval Combatants and Auxiliaries.

Three particular UNREP missions scenarios were examined. These missions included Connected Replenishment (CONREP), Fueling At Sea (FAS), and Vertical Replenishment (VERTREP). Each mission was examined independently of the other. Representative ships from many different naval classes were chosen for the purposes of this study. These ships were: AE36, AO177, BB62, CG47, CGN9, CGN38, CV41, CVN71, DD963, DDG51, FF1052, FFG7, LHD1, LSD41, LST1179, and MCM1.

The seakeeping qualities of a ship can be conveniently predicted using modern strip theory motion programs, such as the Standard Ship Motion Program (SMP84)[1,2]. Work by McCreight and Stahl[3] incorporate environmental data with strip theory motion predictions to calculate Percent Time Operability (PTO). PTO calculations depend heavily on the motion limiting criteria which specify the thresholds of unacceptable motion for a specific mission. PTO calculations allow a relative comparison of ships at specific geographic locations for a given mission. PTOs for Underway Replenishment missions at the GIUK gap* and a representative North Atlantic ocean point† were calculated using the Seakeeping Evaluation Program (SEP)[4].

BACKGROUND

The percent time operabilities (PTOs) estimates for different classes of Navy ships were made using the Seakeeping Evaluation Program (SEP)[4]. PTOs are calculated utilizing the ship transfer functions to predict motion responses as a function of speed, heading, and joint probability of significant wave heights and modal periods. The seaway is modeled by environmental data supplied by the Spectral Ocean Wave Model (SOWM) data base. The SOWM data base contains archived wind data used by the Fleet Numerical Oceanography Center (FNOC) to hindcast wave fields for approximately 1500 locations throughout the northern hemisphere. Each ship response is compared to the limiting criteria in each of the wave spectra which might be encountered in the geographic location of interest. The probabilities of occurrence of the spectra for which none of the motion limits are exceeded are summed to calculate the PTO. The probability of failure is calculated by summing the probabilities of occurrence for each failing wave height-modal period combination. PTO's were calculated using winter season wave data to represent the most severe season in the North Atlantic Ocean.

The criteria sets used to calculate PTOs, consist of motion limits thought to be important to a particular mission, i.e., a response which if exceeded could cause the

*61.1°N; 14.6°W
†55.9°N; 26.7°W

mission to fail[5]. Typical responses chosen as criteria are: roll, pitch, vertical and lateral acceleration, slamming, deck wetness, and propeller racing. The failure limits of the criteria sets are determined by crew habitability, equipment operability, and ship survivability. The specifications for UNREP equipment are high, being empirically determined as fully operable through sea state 5. Through years of experience, tension and loading requirements as applied to Navy replenishment rigs have been found to meet those specifications. The interaction between ship motions and the loads on a connected replenishment rig is not rigorously understood. So, the equipment limits are empirical in nature and the relationship between the equipment specifications and the hydrodynamic loading needs to be investigated. Survivability limits are usually eclipsed by habitability and operability limits which are more conservative.

The accuracy and validity of the PTOs are based on the accuracy of the transfer functions, the motion criteria sets, and wave climatology used in the evaluation. Ship to ship interactions and relative motions between the delivery and receiving ship were not considered in the ship motion calculations. This assumption implies perfect course keeping by both ships, which is not valid for high sea states. No sway or yaw limits were used. The effects of UNREP connections (i.e. span wire rig) which are present in CONREP and FAS were also neglected in the motion calculations. It is the opinion of the authors that the criteria sets indirectly account for the above because information from ship operators were considered during the compilation process. However, criteria sets that directly account for ship to ship interaction and human factors at replenishment stations would have been used if available. Therefore, it must be emphasized that the criteria sets are generic in nature and are independent of the specific replenishment rig. Furthermore, the PTOs represent statistical values and should be treated accordingly. This means a PTO of 80%, represents 80% operability during a 20 year period. It does not mean that for any 5-day period, a ship can successfully operate during 4 of those 5 days.

CONNECTED REPLENISHMENT

Connected Underway Replenishment, an evolution which includes the transfer of personnel, munitions, or cargo between two ships, deserves special attention in terms of seakeeping evaluations. Connected replenishment requires the delivery and receiving ship to steer parallel courses while operating in close proximity to one another. There is little margin for error in terms of shiphandling and collision avoidance between the two ships, which are less than one ship length apart. Severe ship motions, such as slamming and deck submergences, are distracting to the helmsmen and degrade the capability of both ships to remain precisely on course [6]. Crewmembers working at replenishment stations which are located on exposed weather decks are subject to performance degradations due to ship motions, spray, and green water. The criteria set attempts to reflect the degrading effects of severe motions and loss of pallet control. It is interesting to note that the criteria sets indicate that the major motion limits associated with CONREP are associated with moving the stores once they are aboard the receiving ship, rather than during the actual transfer from ship to ship. The CONREP mission criteria is given below. The SEP results for the representative fleet are given in Table 1 and Fig. 1.

CRITERION	LIMIT
Roll	5° Significant Single Amplitude
Pitch	2° Significant Single Amplitude
Absolute Vertical Accel	0.4 g's Significant Single Amplitude
Absolute Lateral Accel	0.2 g's Significant Single Amplitude
Wetnesses at station 0	30 per hour
Slams at station 3	20 per hour
Propeller racing	90 per hour

FUELING AT SEA

Fueling at Sea (FAS) is similar to CONREP in that the delivery and receiving ships are connected, but only fuel is transferred. The difficulties associated with ship handling and crew exposure to adverse conditions are still present. Since only fuel is delivered during this evolution, pallet control does not become an issue. The roll limit of the criteria set, which follows, reflects the limits relating to the transfer of fuel through a hose between two ships, rather than the movement of supplies on pallets. The results are presented in Table 2 and Fig. 2.

CRITERION	LIMIT
Roll	6° Significant Single Amplitude
Pitch	2° Significant Single Amplitude
Absolute Vertical Accel	0.4 g's Significant Single Amplitude
Absolute Lateral Accel	0.2 g's Significant Single Amplitude
Wetnesses at station 0	30 per hour
Slams at station 3	20 per hour
Propeller racing	90 per hour

VERTICAL REPLENISHMENT

Vertical replenishment (VERTREP) involves the use of a helicopter to transport stores rather than cranes and cables between connected ships. This evolution can be conducted in conjunction with CONREP and FAS or can be performed independently. VERTREP permits the total replenishment of ships in a dispersed formation which do not require fuel and has the major advantage of not requiring a physical connection between the transferring ship and receiving ship. Since VERTREP helicopters are often not maintained aboard the receiving ships, this study assumes that the helicopters were successfully launched from the mother ship. This may not be a valid assumption in the higher sea states. The delivery of cargo only requires that the helicopter retains the capability to hover above the deck of the UNREP ship to raise or lower cargo pallets.

A major factor in VERTREP is the requirement of a high relative wind to facilitate hovering of the helicopter. An optimum and non-optimum relative wind envelope for VERTREP exist. The operability assessments used the non-optimum relative wind envelope, see Fig. 3. The less restrictive non-optimum envelope gives the total possibility of conducting VERTREP rather than possibility of easily conducting VERTREP with the optimum wind envelope. The motion limits, given below, reflect pallet control and severe motion limits rather than limits associated with the transfer of equipment between connected ships. For vertical replenishment results, see Table 3 and Fig. 4. Normalized PTO calculations only consider speed-heading combinations that produce the desired relative wind. In other words, the ship is assumed to be in the relative wind envelope before motion criteria are applied. The un-normalized results use all speed-heading combinations.

CRITERION	LIMIT
Roll	5° Significant Single Amplitude
Pitch	3° Significant Single Amplitude
Absolute Vertical Accel	0.4 g's Significant Single Amplitude
Absolute Lateral Accel	0.2 g's Significant Single Amplitude
Wetnesses at station 0	30 per hour
Slams at station 3	20 per hour
Propeller racing	90 per hour

RESULTS

Three UNREP mission criteria sets were applied to 16 Navy ships, representative of the Fleet. The three UNREP mission criteria sets represent Connected Replenishment, Fueling Along Side, and Vertical Replenishment. By examining the PTOs of each mission for each ship, it is possible to determine fleet wide trends regarding Underway Replenishment.

For all UNREP missions, the larger the displacement, the better the performance. As an example, the PTOs for the CONREP mission are plotted versus displacement in Fig. 5. The second variable that indicated good seakeeping performance was length, causing the CGN9 to perform as well as the AE36, see Fig. 6. Increasing length and displacement have long been acknowledged to improve seakeeping. So for most UNREP evolutions, the smaller combatant limits operations rather than the auxiliary. When replenishing larger combatants and amphibious ships, the auxiliaries become the limiting ship because of their motions. So attention should continue to be focused on improving the seakeeping capacity of the small to medium sized combatants.

The time limited by criteria other than roll and pitch was minimal. For CONREP and VERTREP missions, roll was the most limiting motion. With the FAS mission, ten of seventeen were most limited by pitch. The PTOs for FAS are slightly higher, because of the higher roll limit. That the PTOs did not change much means the limiting wave height for the roll and pitch criteria are nearly equal, with pitch being slightly higher. A one degree reduction in significant single amplitude roll would raise the CONREP PTOs to the FAS level. As only one ship, the FFG7, was equipped with active anti-roll fins, improvement in roll reduction seems promising. Reducing pitch motion is more difficult due to the large forces involved and the broad band response of pitch. Pitch is typically reduced by a constrained optimization of the hull early in the design process. Investigations to reduce pitch by means of appendages, e.g., bow fins, canted rudders, or stern fins, continue. Assuming motions cannot be reduced, increasing the effective pallet limit one degree would make the CONREP and FAS criteria sets and PTOs identical. So where the PTOs are limited by the movement of pallets on the deck, the two ways to increase operability are either reduce the motions or improve the pallet's controllability for the present motions.

With VERTREP the question of relative wind arises. If only speed-heading combinations that produce the desired relative wind are examined, the PTOs are much higher than either the CONREP or FAS PTOs. This is because those combinations exclude the region where most of the pitch limitation is occurring. So by examining a selected set of speed-heading combinations, the ones that yield the relative wind envelope, most of the limitation due to pitch is eliminated with a corresponding increase in PTO. The improvement decreases with increasing displacement from a 20 to 10 percentage point improvement.

If all speed-heading combinations are considered, regardless of relative wind, the benefits of conducting VERTREP instead of CONREP are not so clear cut. The relative wind envelope can be either helpful or hurtful depending on whether it excludes combinations of low or high operability. The slightly larger motion limits are only a boon, if the ship was barely failing with the lower limits. If the ship is well under the lower motion limits associated with CONREP, they will be well under the VERTREP higher limits with little increase in operability. Similarly, if the ship has very low operability, a slight relaxation of the motion limits, will not appreciably improve the situation. Therefore, the attractiveness of conducting VERTREP depends on which speed-heading combinations are excluded by the relative wind envelope and how badly the motions exceed the criteria.

A third of the ships examined had higher VERTREP PTOs than CONREP or FAS PTOs; a third were about the same; and a third were worse. Those that still maintained an advantage over CONREP and FAS were AO177, CG47, DDG51, FF1052, and MCM1. These ships benefited from having slightly relaxed motion limits and a relative wind envelope. With the larger ships of this group, AO177, CG47, DDG51, and FF1052, the improvements are more the result of higher criteria limits. If they were just failing a given wave height before, they are probably just passing now with increased PTO. The MCM1 derives its improvement from helpful relative wind effects and showed the largest improvement.

The third that had about the same PTOs for all three missions were AE36, CGN9, CGN38, DD963, LSD41, and FFG7. These are mainly the medium displacement ships. Here the advantages of increased limits is counterweighted by adverse effects of the relative wind envelope. The third that were worse at VERTREP than CONREP and FAS consisted of the larger ships, BB62, CV41, CVN71, LHD1, and LST1179. These ships were penalized by the relative wind envelope and could not take advantage of the higher motion limits because of already good seakeeping. Regions of high operability were negated by the relative wind envelope.

CONCLUSIONS

There are definite preferred methods of UNREP depending on ship size. The ability to conduct CONREP and FAS missions are about the same, despite the CONREP criteria being based on pallet control limits and the FAS criteria based on the transfer equipment. The ships with good seakeeping should use CONREP to avoid relative wind penalties. Conversely, CONREP and FAS are to be avoided by poor seakeeping ships because the higher motion limits allowed with VERTREP. This study also shows the advantage of improving pallet design, e.g. rails on deck.

For all three UNREP missions, CONREP, FAS, and VERTREP, operability increases with increasing displacement and length. As a result, UNREP missions are usually dependent upon the motions of the smaller ship. Therefore, auxiliaries should continue to be large to maintain their superior seakeeping and not become a limiting factor in UNREP. Roll and pitch were the two motions that limited operability most. As roll is relatively easier to reduce than pitch, some form of roll reduction device seems appropriate.

That roll and pitch were the most limiting criteria is a reflection of the criteria sets used. Roll and pitch are traditionally specified because of the relative ease of measuring them, even though they may not be strictly appropriate. That vertical acceleration is not a limiting motion may be an indication that the limit is too high. For missions with location dependent tasks, criteria that deal with a certain task and location would be more appropriate than ship wide criteria such as roll and pitch. Also the sources of degradation, spray, slippery decks, stumbling, are ignored with the current criteria sets. Furthermore, these criteria sets assume ideal conditions, static heel, dry decks, a fresh and alert crew, when determining threshold limits. Thus, different criteria dealing specifically with human factors, i.e. motion induced interruptions, and non-ideal conditions need to be verified and applied.

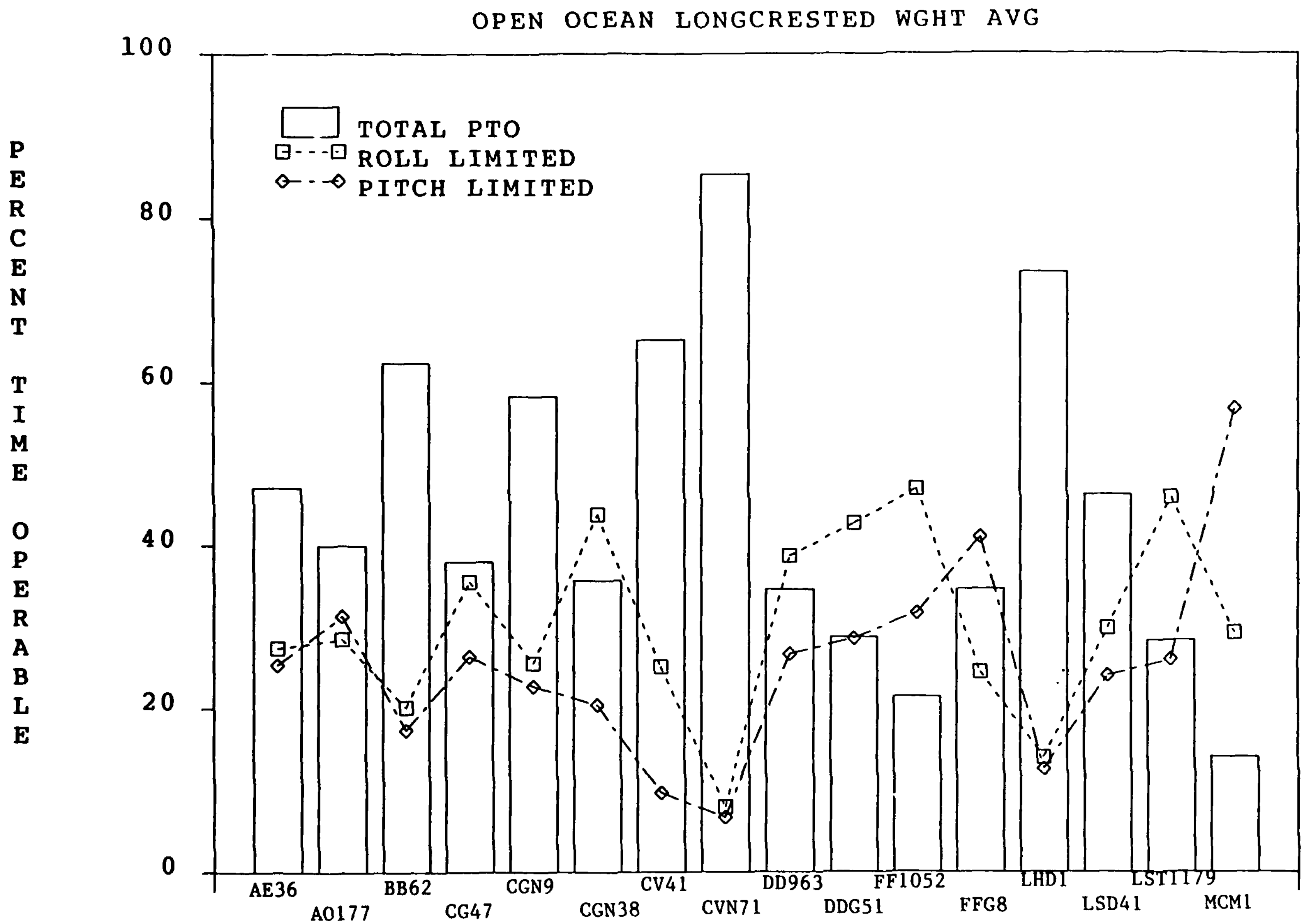

Fig. 1. Connected Replenishment operability results by ship class.

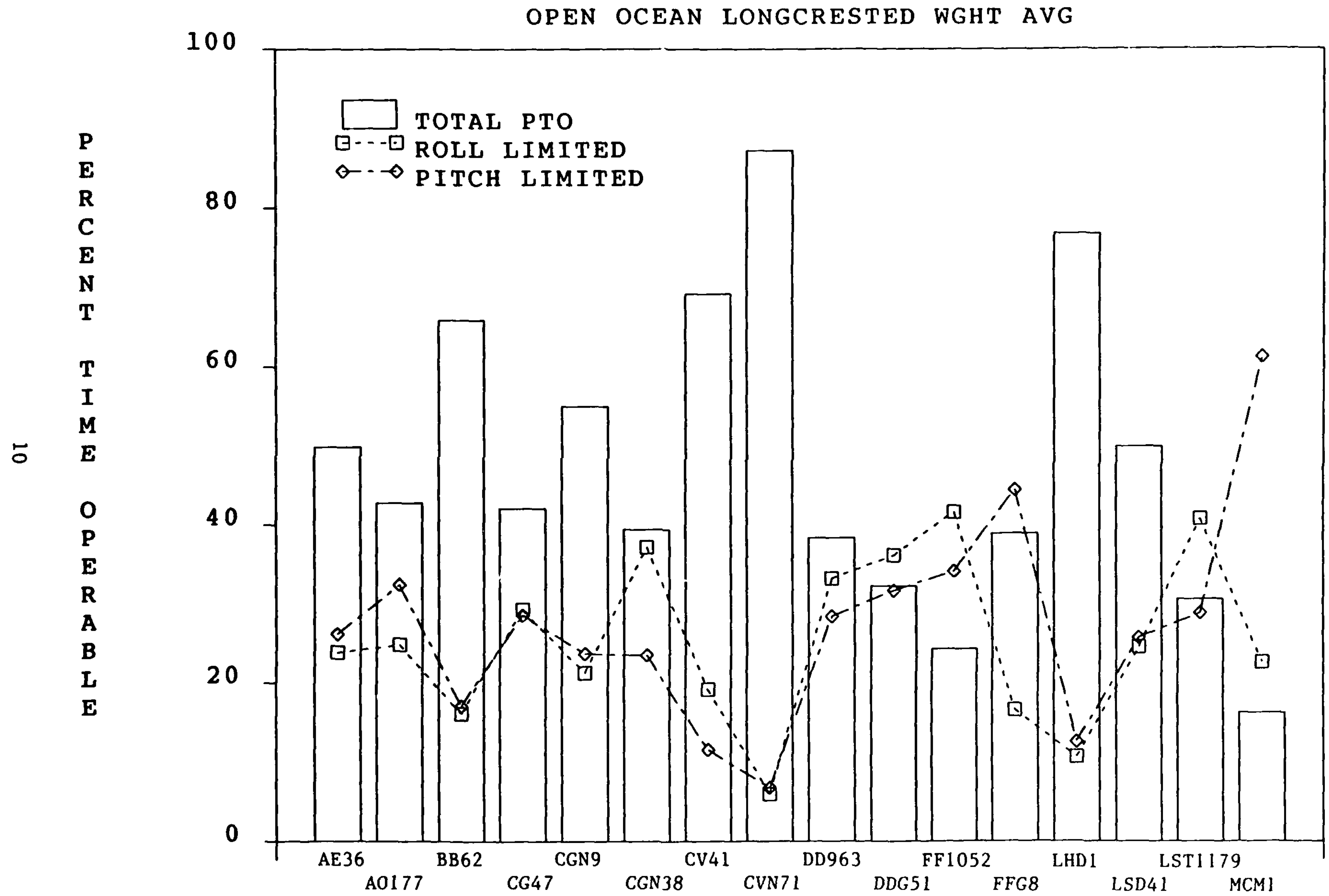

Fig. 2. Fueling At Sea operability results by ship class.

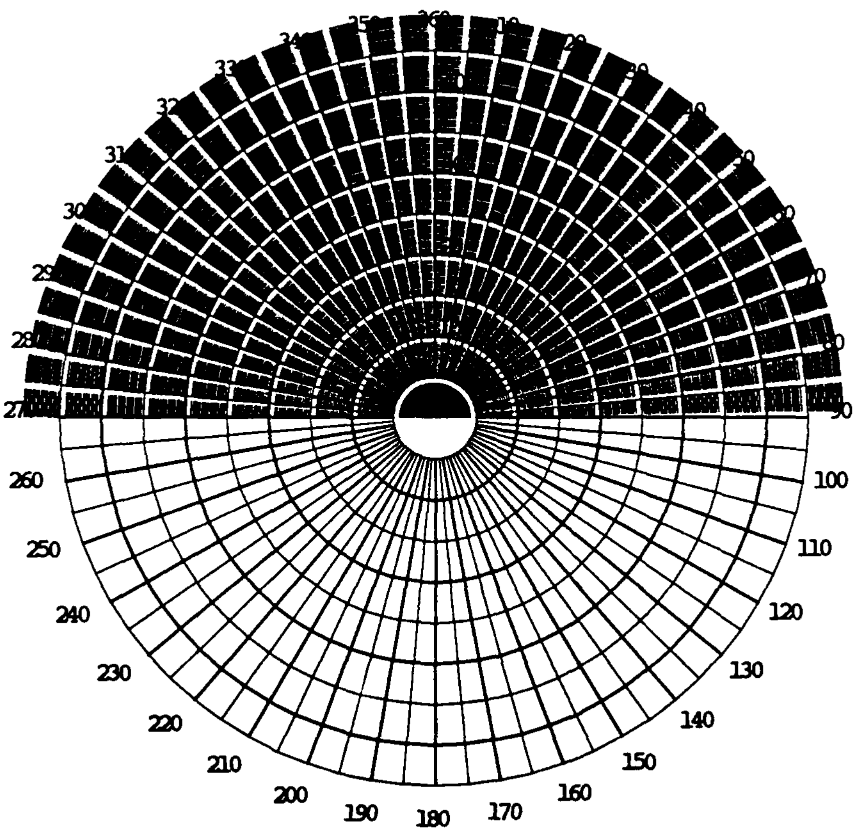

Fig. 3. Relative wind envelope used for Vertical Replenishment assessments.

Note: Shaded area indicates acceptable relative wind.

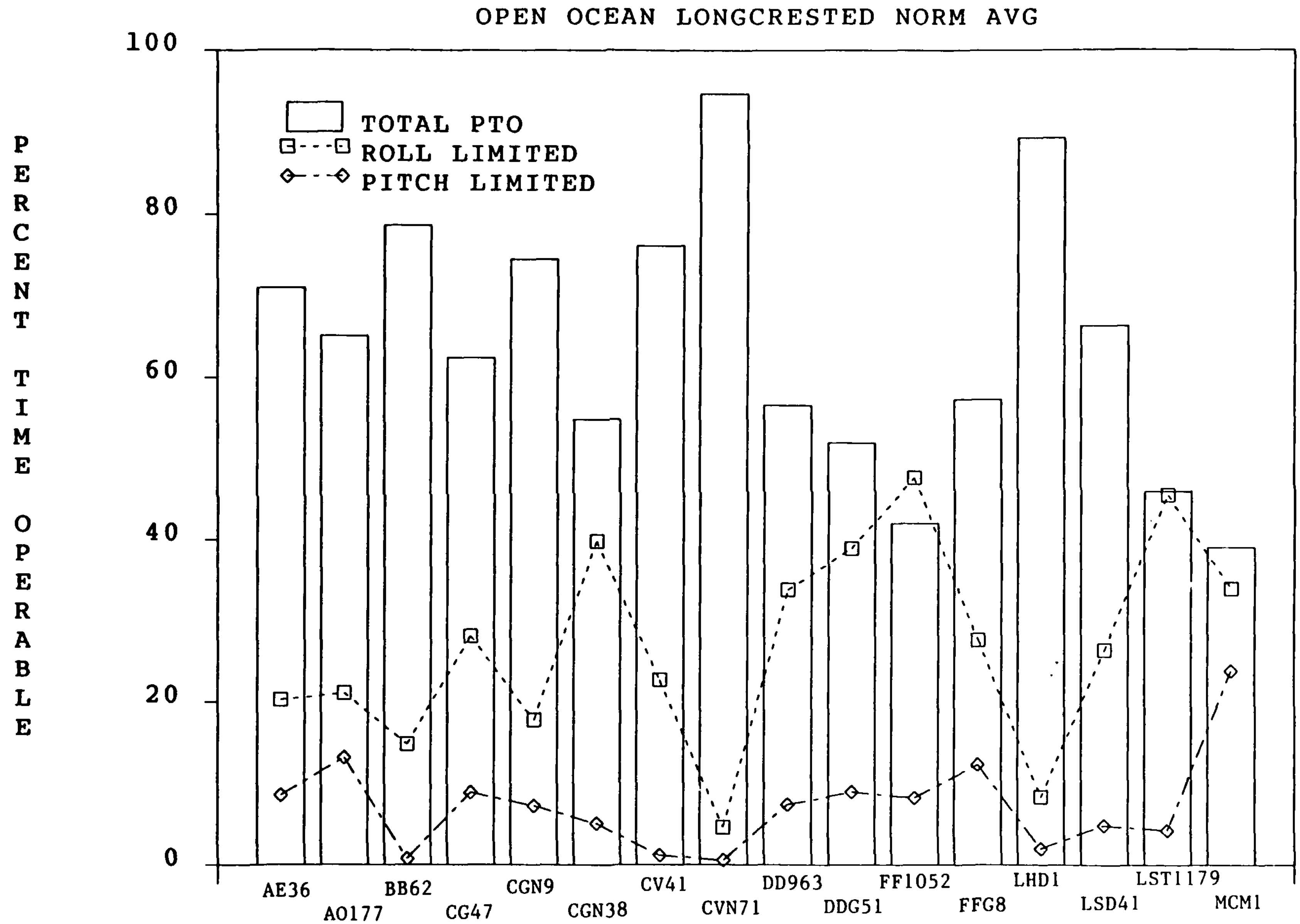

Fig. 4. Vertical Replenishment operability results by ship class.

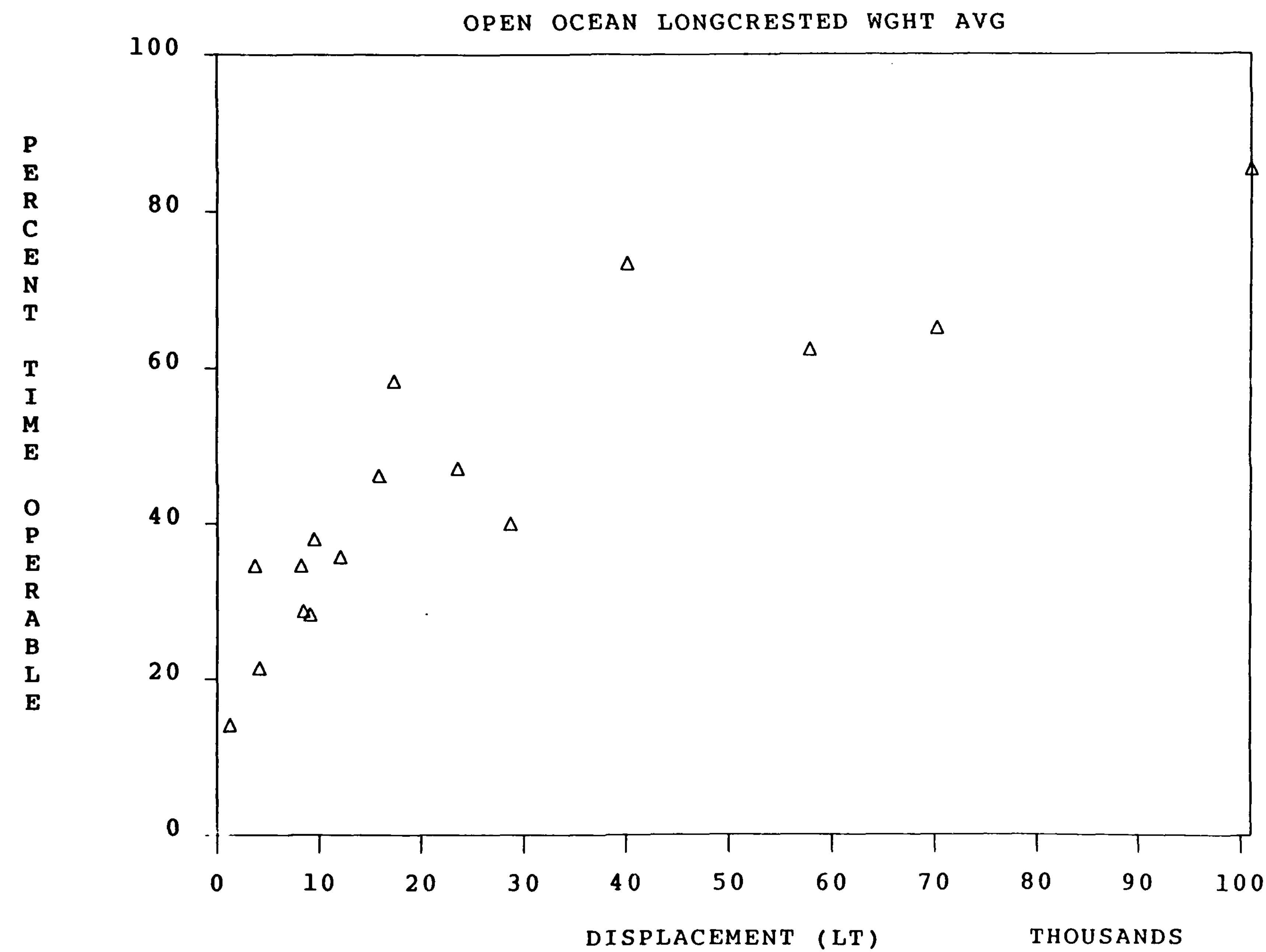

Fig. 5. Connected Replenishment operability results by ship displacement.

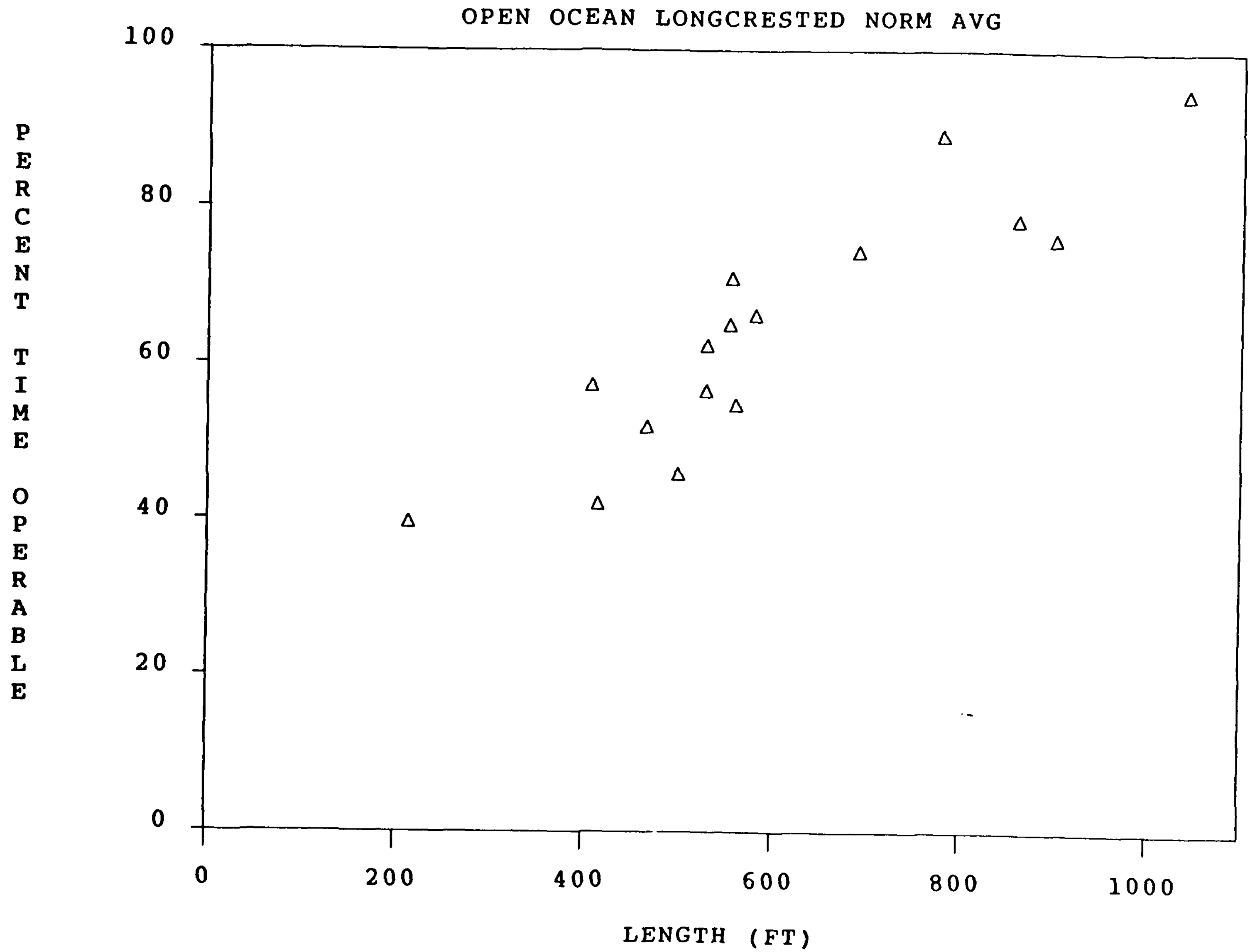

Fig. 6. Vertical Replenishment operability results by ship length.

Table 1. Connected Replenishment operability results.

• Percent Time Operable, GIUK Gap[1], Winter, CONREP Mission

	BB62	CG47	CGN9	CGN38	CV41	CVN71	DD963	DDG51	FF1052	FFG7fins
Total PTO	70.3	46.5	59.9	44.1	73.0	90.0	43.0	37.1	29.5	44.1
PTO Roll Limited	16.6	31.1	21.9	39.2	20.9	6.1	34.5	38.5	42.9	20.7
PTO Pitch Limited	13.0	22.4	18.2	16.7	6.1	4.0	22.5	24.4	27.6	35.2

	LHD1	LSD41	LST1179	AE36	AO177	MCM1
Total PTO	81.0	55.1	36.7	55.2	48.3	22.1
PTO Roll Limited	10.8	25.9	41.9	24.1	25.0	26.3
PTO Pitch Limited	8.2	19.0	21.4	20.7	26.7	51.6

• Percent Time Operable, Open N. Atl[2], Winter, CONREP Mission

	BB62	CG47	CGN9	CGN38	CV41	CVN71	DD963	DDG51	FF1052	FFG7fins
Total PTO	62.4	38.0	51.6	35.7	65.2	85.3	34.6	28.7	21.4	34.6
PTO Roll Limited	20.2	35.6	25.6	43.9	25.1	7.9	38.7	42.7	46.9	24.4
PTO Pitch Limited	17.4	26.4	22.8	20.5	9.7	6.7	26.7	28.6	31.7	41.0

	LHD1	LSD41	LST1179	AE36	AO177	MCM1
Open N. Atl.	73.4	46.2	28.3	47.1	40.0	14.1
PTO Roll Limited	14.0	29.8	45.8	27.4	28.6	29.2
PTO Pitch Limited	12.6	24.0	26.0	25.4	31.4	56.7

[1](61°N; 15°W) [2](56°N; 27°W)

Table 2. Fueling At Sea operability results.

- Percent Time Operable, GIUK Gap[1] Winter, FAS Mission

	BB62	CG47	CGN9	CGN38	CV41	CVN71	DD963	DDG51	FF1052	FFG7fins
Total PTO	74.0	51.0	63.4	48.1	77.2	91.7	47.2	41.0	32.8	48.3
PTO Roll Limited	12.5	25.0	17.8	32.8	15.4	4.3	28.9	32.1	37.5	13.8
PTO Pitch Limited	13.5	24.0	18.8	19.1	7.4	4.0	23.9	26.9	29.6	37.9

	LHD1	LSD41	LST1179	AE36	AO177	MCM1
Total PTO	84.0	59.0	39.4	58.0	51.3	24.6
PTO Roll Limited	7.7	20.9	36.8	20.6	21.2	20.0
PTO Pitch Limited	8.3	20.2	23.8	21.3	27.5	55.4

- Percent Time Operable, Open N. Atl[2] Winter, FAS Mission

	BB62	CG47	CGN9	CGN38	CV41	CVN71	DD963	DDG51	FF1052	FFG7fins
Total PTO	65.9	42.1	55.0	39.4	69.2	87.2	38.3	32.2	24.3	38.9
PTO Roll Limited	16.1	29.3	21.3	37.2	19.2	6.0	33.2	36.1	41.6	16.6
PTO Pitch Limited	17.1	28.6	23.7	23.5	11.6	6.8	28.4	31.7	34.1	44.4

	LHD1	LSD41	LST1179	AE36	AO177	MCM1
Total PTO	76.7	49.9	30.5	49.9	42.8	16.2
PTO Roll Limited	10.7	24.5	40.7	23.9	24.8	22.6
PTO Pitch Limited	12.6	25.7	28.8	26.2	32.4	61.2

[1](61°N; 15°W) [2](56°N; 27°W)

Table 3. Vertical Replenishment operability results.

• Percent Time Operable, GIUK Gap[1], Winter, VERTREP Mission

Ship	BB62	CG47	CGN9	CGN38	CV41	CVN71	DD963	DDG51	FF1052	FFG7fins
Total PTO Norm	83.6	69.3	79.9	61.5	80.5	95.7	63.6	59.2	48.7	64.4
PTO Roll Limited	12.3	23.6	15.1	34.7	18.8	4.0	29.3	3.4	42.9	23.6
PTO Pitch Limited	0.5	6.5	4.5	3.5	0.7	0.4	5.3	6.8	6.6	9.7
Total PTO Un-Norm	62.6	50.7	60.2	42.8	59.0	74.0	45.9	41.3	31.8	45.8

Ship	LHD1	LSD41	LST1179	AE36	AO177	MCM1
Total PTO Norm	91.9	72.6	51.9	76.6	71.3	46.9
PTO Roll Limited	6.7	22.3	41.0	17.6	18.1	30.0
PTO Pitch Limited	1.2	3.0	3.3	5.7	10.0	20.3
Total PTO Un-Norm	70.5	52.5	33.5	57.0	51.7	28.8

• Percent Time Operable, Open N. Atl.[2], Winter, VERTREP Mission

Ship	BB62	CG47	CGN9	CGN38	CV41	CVN71	DD963	DDG51	FF1052	FFG7fins
Total PTO Norm	78.6	62.4	74.5	54.8	76.1	94.7	56.6	52.0	42.1	57.3
PTO Roll Limited	14.8	28.1	17.8	39.8	22.7	4.6	33.9	39.0	47.7	27.7
PTO Pitch Limited	0.8	8.9	7.3	5.1	1.2	0.6	7.4	9.0	8.3	12.4
Total PTO Un-Norm	56.0	43.2	53.6	35.4	52.8	71.1	38.5	33.7	24.9	38.2

Ship	LHD1	LSD41	LST1179	AE36	AO177	MCM1
Total PTO Norm	89.3	66.3	45.9	71.0	65.1	39.7
PTO Roll Limited	8.4	26.4	45.5	20.3	21.1	33.9
PTO Pitch Limited	2.0	4.9	4.3	8.6	13.2	23.8
Total PTO Un-Norm	66.0	44.9	26.7	50.2	44.5	20.7

[1](61°N; 15°W) [2](56°N; 27°W)

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