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USS AVENGER (MCM 1) Standardization, Locked Shaft, and Trailed Shaft Trials

by

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CARDEROCKDIV-92/007 USS AVENGER (MCM 1) Standardization, Locked Shaft, and Trailed Shaft Trials

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Standardization, Trailed Shaft, and Locked Shaft Trials were conducted on USS AVENGER (MCM 1) to develop baseline speed and powering characteristics for the MCM 1 class minesweepers. The trials were performed off the west coast of St. Croix, U.S. Virgin Islands from 19 to 22 June 1989 as part of NAVSEA First of Class Performance Trials. During the Standardization Trial a maximum speed of 13.92 kn at 181.7 r/min average shaft speed was achieved with the propellers at nominal 100% of design pitch. To achieve this speed, AVENGER required 2,050 total shaft horsepower (1,530 kW), with 59,300 ft-lbf total torque (80,300 N-m) applied to the shafts. The maximum speed achieved during the Locked Shaft Trial was 9.13 kn with the port shaft driving the ship at a shaft speed of 167.2 r/min. At this speed the AVENGER used 970 hp (720 kW) and 30,400 ft-lbf of torque (41,200 N-m) on the driving shaft. During the Locked Shaft Trial, the pitch on the port propeller was at nominal 100%, while the pitch on the locked starboard shaft propeller was nominal 15%. For the Trailed Shaft Trial a maximum speed of 10.34 kn was achieved at 168.5 r/min shaft speed on the driving port shaft. This speed was accomplished with 980 hp (730 kW) and 30,300 ft-lbf torque (41,100 N-m)

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on the driving shaft. During the Trailed Shaft Trial nominal 100% pitch was used on the port propeller with the starboard propeller trailing at nominal 110% pitch.

Baseline standardization, trailed shaft, and locked shaft curves are also developed for the AVENGER in this report.

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USS AVENGER (MCM 1)

ABSTRACT

Standardization, Trailed Shaft, and Locked Shaft Trials were conducted on USS AVENGER (MCM 1) to develop baseline speed and powering characteristics for the MCM 1 class minesweepers. The trials were performed off the west coast of St. Croix, U.S. Virgin Islands from 19 to 22 June 1989 as part of NAVSEA First of Class Performance Trials. During the Standardization Trial a maximum speed of 13.92 kn at 181.7 r/min average shaft speed was achieved with the propellers at nominal 100% of design pitch. To achieve this speed, AVENGER required 2,050 total shaft horsepower (1,530 kW), with 59,300 ft-lbf total torque (80,300 N-m) applied to the shafts. The maximum speed achieved during the Locked Shaft Trial was 9.13 kn with the port shaft driving the ship at a shaft speed of 167.2 r/min. At this speed the AVENGER used 970 hp (720 kW) and 30,400 ft-lbf of torque (41,200 N-m) on the driving shaft. During the Locked Shaft Trial, the pitch on the port propeller was at nominal 100%, while the pitch on the locked starboard shaft propeller was nominal 15%. For the Trailed Shaft Trial a maximum speed of 10.34 kn was achieved at 168.5 r/min shaft speed on the driving port shaft. This speed was accomplished with 980 hp (730 kW) and 30,300 ft-lbf torque (41,100 N-m) on the driving shaft. During the Trailed Shaft Trial nominal 100% pitch was used on the port propeller with the starboard propeller trailing at nominal 110% pitch.

Baseline standardization, trailed shaft, and locked shaft curves are also developed for the AVENGER in this report.

ADMINISTRATIVE INFORMATION

As of January 1992, the David Taylor Research Center (DTRC) became the Carderock Division, Naval Surface Warfare Center (CARDEROCKDIV, NSWC). However, throughout this report CARDEROCKDIV, NSWC will be referred to as DTRC. The work described herein was performed by DTRC, Code 1523. This project was carried out under DTRC Work Unit 1523-517. The funding source was the Naval Sea Systems Command (NAVSEA), PMS 303.

INTRODUCTION

The information contained in this report was previously reported in a report of higher classification.*

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* Boboltz, David A., Jr., David Taylor Research Center, as reported in DTRC-90/002, a report of higher classification.

USS AVENGER (MCM 1) is the first in a series of mine countermeasure ships being built for the U.S. Navy. Built by Peterson Builders Inc. of Sturgeon Bay, Wisconsin, the ship, was commissioned on 12 September 1987, and is powered by 4 Waukesha LN 1616 DSIN diesel engines geared to two Transamerica-Delaval reduction gears. In addition to the diesel engines, the AVENGER may also be powered by two light load electric motors built by Hansome Energy Systems, Inc. The propellers for AVENGER are Bird-Johnson controllable reversible pitch propellers. The principal ship and propeller characteristics for the AVENGER are given in Table 1.

Standardization, Trailed Shaft, and Locked Shaft Trials were conducted on AVENGER at a tracking site off the west coast of St. Croix, U.S. Virgin Islands as part of First of Class Special Performance Trials. A full description of this tracking site can be found in Appendix A. These trials provided a baseline for comparison of future trials on the MCM 1 class of ships.

TRIAL CONDITIONS

This section will discuss the environmental conditions and the condition of the ship's hull during the trials. Conditions for the Standardization, Locked Shaft, and Trailed Shaft Trials are presented in Table 2.

For the Standardization Trial, wind conditions were considered good, with wind speeds ranging between 8.3 and 20.8 kn. The limit for wind speeds that are acceptable for the conduct of DTRC sea trials is 20 kn. During the two days of Standardization testing, sea conditions were considered good, with conditions varying between sea state 0 and sea state 1.

For the Locked Shaft and Trailed Shaft Trials, wind conditions were considered good, with true wind speeds ranging between 7.9 and 20.4 kn. During the one day of Locked and Trailed Shaft testing, sea conditions were considered good, again varying between sea state 0 and sea state 1.

Displacement and trim were calculated based on draft readings taken pierside. The displacement of the AVENGER during the Standardization trial was found to be 1288 tons (1309 t), and the trim was found to be 1.33 ft (0.41 m) down by the stern. The displacement of the AVENGER during the Locked and

Trailed Shaft Trials was calculated to be 1280 tons (1301 t), and the trim was found to be 1.66 ft (0.51 m) down by the stern. A more in-depth discussion of how the displacement and trim were obtained can be found in Appendix B.

A hull roughness survey was conducted on AVENGER 8 days prior to testing. This survey indicated that AVENGER's hull condition was suitable for the performance of U.S. Navy sea trials. Appendix C contains a more detailed analysis of the ship's hull condition.

TRIAL PROCEDURES

The Standardization, Trailed Shaft, and Locked Shaft Trials were conducted in accordance with Chapter 094 of the Naval Ship's Technical Manual.

Speed/powering curves were defined by comparing range determined ship speeds to ship powering conditions (shaft speed, shaft torque, shaft power) throughout the speed range with various powering conditions being applied. The ship normally operates with the propeller pitch control systems set in the program control mode which adjusts the propeller pitches to predetermined values according to shaft speed. For the Standardization, Locked Shaft, and Trailed Shaft Trials, the propeller pitch control systems were set in the manual mode which allows propeller pitch and shaft speed to be adjusted independently. The control systems were set in the manual mode so that propeller pitch could be trimmed to compensate for variations due to changes in the pitch control system hydraulic oil temperature.

During the trials, two to three runs were made in opposing directions for each selected speed. The average of these runs made in reciprocal directions at the same power level is defined as a spot. It can be seen in Tables 4 through 9 that a two pass spot was made on two occasions. A two pass spot is acceptable if the gradient in the current is determined to be smaller than 0.2 kn and the magnitude of the current is less than 0.5 kn prior to the running of the spot. The runs which make up each spot were averaged using mean of means averaging to come up with a speed for the ship which contained no contributions due to current.

Each run was initiated when ship speed, shaft torque, and shaft speed reach steady predetermined values. One minute of steady approach data were collected and then three minutes of steady run data were recorded. Minimum rudder movement, generally ± 3°, is used to maintain heading during the approach and the actual run. During the run, shipboard ranging equipment recorded time and ship position relative to two predetermined reference points on shore. Range data was then coupled to machinery data to determine speed and powering relationships for each run. This trial procedure was the same for the Standardization, Locked Shaft, and Trailed Shaft Trials. A more in-depth discussion of trial procedures may be found in DTRC report DTRC/SHD-1320-01.[1]

INSTRUMENTATION

Measurements taken for each run during the trials were ship speed, ship position, ship heading, rudder position, shaft torque, wind speed, wind direction, propeller pitch, pitch control system oil temperature, shaft torque, and shaft rotational speed. Shaft horsepower was calculated based on measured shaft speed and torque. A Hewlett Packard (HP) 300 computer with an HP 3852A measurement and control processor converted analog voltages to digital signals and stored them on flexible disks. The computer calculated the run averages as well as the maximum and minimum values. The data were also converted into engineering units and displayed in a hard copy format as output from a line printer. Figure 1 shows the data acquisition system used on AVENGER.

Ship's speed was both calculated and recorded directly. The Motorola Falcon 484 pulse radar positioning system recorded both the ship's x and y coordinates relative to the range, and the time between positional readings. From these, it calculated the range speed of the ship. A more detailed discussion of the ship speed calculation is given in Appendix A. In addition to the calculation of ship speed by range, the ship's electromagnetic (EM) speed log was recorded by paralleling the ship's EM log synchro repeater in the chart room.

Ship heading and rudder position, in addition to EM log, were recorded using ship's synchro signals. These three phase, 60-cycle, signals were converted to analog voltages using a synchro to analog (S/A) converter. The analog voltages were then input to the computer via the HP 3852A processor discussed earlier.

Wind speed and wind direction were recorded using a wind anemometer provided by DTRC, and mounted on the jack mast on the bow of the ship. The synchro signals from the wind anemometer were input to the S/A converter and the resulting analog voltages were then provided to the computer as described above.

Propeller pitch was recorded using the analog voltage signal from the shaped potentiometer in the engine room. This pitch signal was corrected for variations in the temperature of the pitch control system hydraulic oil. This temperature, indicated by a ship's gage located in the hydraulic oil pressure manifold (HOPM), was recorded manually during the propeller pitch calibration and during each run of the trials. A more in depth discussion of the propeller pitch and corrections to the pitch due to variations in hydraulic oil temperature, ambient sea water temperature, and thrust compression is provided in Appendix D.

An Acurex 1645 torque monitoring system, mounted on each propeller shaft, was used to measure shaft torque. Two carrier rings were clamped on each flexible coupling approximately 9 in. aft of the reduction gear and were used to transmit the torque on the shaft to a sensor bar. The sensor bar is a sealed metal tube containing a strain gage bridge which measured the torque on the shaft as a deflection of the bar. A stationary electronics unit induced voltage and current required to drive the rotating electronics and strain gage bridge. The output of the bridge was connected to a rotating low power transmitter. The transmitter signal was received, demodulated, and conditioned by the stationary unit, thus producing an analog voltage proportional to torque. The Acurex torque measurement system was calibrated by subjecting the sensor bar to precise displacement increments which are related to shaft torque by known properties such as outside diameter, inside diameter, and modulus of rigidity.

In addition to the torque measurement system described above, another system was used by DTRC to measure shaft torque during the trials on AVENGER. This system, the Acurex 1200 system, is based on the same principal as the

1645 system except that the strain gage bridge was bonded directly to the shaft and connected to a rotating transmitter clamped on the shaft. On previous MCM class trials, only the 1200 systems had been used due to space restrictions. This system was mounted in a 6 in. (15.24 cm) space on the intermediate shaft just forward of the oil distribution box. When it was determined by DTRC personnel that there was sufficient room to mount the 1645 system on the flexible coupling, it was decided that both systems would be used for the trials on MCM 1. It was thought that mounting two systems on each shaft would provide a comparison of the two DTRC torque measurements. Appendix E provides a comparison of the two DTRC torque measurement systems. It was intended that the ship's permanent torsionmeters be included in the comparison shown in Appendix E, but at the time of the trials, they were inoperable.

Shaft rotational speed (r/min) was obtained using an infrared light sensor mounted adjacent to each shaft. A mylar band was wrapped around and secured to each shaft. Attached to this band were sixty equally spaced pieces of reflective tape, each separated by a non-reflective surface. As the shaft rotated, a pulse was generated each time a tape strip passed the sensor. The pulses were generated at a frequency directly proportional to shaft speed. This pulse train was converted to an analog voltage with a frequency to voltage (F/V) converter.

Accuracies associated with DTRC trial measurements are provided in Table 3. It should be noted that the 1.5% full scale accuracy specified for the 1645 torque measurement system includes an allowance of ±0.8% full scale for the accuracy of the propulsion shaft modulus of rigidity. A handbook value for the modulus of rigidity of 6.58×10^6 psi (45.4×10^6 kPa) was used. Modulus of rigidity measurements obtained on the flexible couplings of MCM 3 through MCM 11, subsequent to the subject trials, however, indicate a variation in modulus of rigidity from shaft to shaft well in excess of ±0.8% full scale. The 1645 torque measurement accuracy is therefore suspect.

PRESENTATION AND DISCUSSION OF RESULTS

BACKGROUND

The results of the Standardization, Locked Shaft, and Trailed Shaft Trials are graphically presented in Figs. 2, 3, and 4, and are tabulated in Tables 4 through 9. In Tables 4 through 9 it can be seen that the port and starboard shaft torque measurements were recorded with two different systems. The starboard torques used in the tables were recorded by the Acurex 1645 system while the port torques used in the tables were recorded by the Acurex 1200 system. It can be seen in Table 3 that the 1645 system is normally the more accurate of the two systems and is therefore the more desirable system to use. When the data was tabulated and plotted for both systems, it was found that the port torque recorded by the 1645 system was considerably higher than that recorded by the 1200 system installed on the port shaft. The torque recorded by the port 1200 system was close to those measured by both the 1645 system and the 1200 system on the starboard shaft. This relationship can be seen in Fig. E.1 and Table E.1.

The difference between the torque measurements meant that either the port torque recorded by the 1645 system was correct, which would indicate that at balanced shaft speed and propeller pitch there is a significant shaft torque imbalance, or that the port 1645 system, normally the more accurate of the two systems, was incorrect. Upon returning from the trial both Acurex 1645 systems were calibrated a second time. Both systems were found to be in good calibration, and no significant problems were found with the port system to indicate bad torque readings. There was, therefore, no reason to discount the measurements from the port 1645 system. The data from previous trials were then checked for a similar imbalance which would indicate that the readings from the 1645 system were correct. Data from Builders and Acceptance Trials on MCM 1, MCM 2, MCM 3, and MCM 5 were all checked. The systems used for Builders and Acceptance Trials on the above ships are as follows:

Ship	1200 System	1645 System
MCM 1	X	
MCM 2	X	X
MCM 3	X	
MCM 5		X

Throughout all the data no significant torque imbalance could be found. Based on this fact and the fact that the port 1200 system agreed with both systems on the starboard shaft within the accuracies of the systems, it was decided that the 1200 system torque data would be presented as the true torque on the port shaft for the Standardization, Locked Shaft, and Trailed Shaft Trials.

During the above Builders and Acceptance Trials, it was found that the inside diameter and modulus of rigidity of the sections of shaft, upon which the 1645 system is mounted, vary from ship to ship. Since the inside diameter and modulus of rigidity of the shafting upon which both 1645 systems were mounted have not been confirmed by direct measurement, it is believed that this variation could be the cause of the high torque readings from the port 1645 system. The modulus of rigidity and the inside diameter of each shaft is used in the calibration of both torsionmeter systems, but the 1645 systems were mounted on sections of shafting which seem to have poorer quality control resulting in the variations of these two parameters.

STANDARDIZATION TRIAL

The Standardization Trial on AVENGER was conducted on 19 and 20 June 1989 at a displacement of 1288 tons (1309 t) and a trim of 1.33 ft (0.40 m) down by the stern. The primary purpose of the Standardization Trial was to determine the speed/powering characteristics of an MCM 1 class ship and to provide a baseline for future trials on the class. The maximum design shaft torque for the AVENGER is 34,400 ft-lbf (46,600 N-m), and the maximum design shaft speed is 180.0 r/min.

The results of the Standardization Trial are graphically presented in Figs. 2 and 3, and are tabulated in Tables 4 and 5. Fig. 2 shows speed and power data collected between 7.16 kn and 13.92 kn. The maximum standardization performance achieved was:

Ship speed by range	-	13.92 kn
Average shaft speed	-	181.7 r/min
Total shaft torque	-	59,300 ft-lbf (80,300 N-m)
Total shaft power	-	2,050 hp (1,530 kW)
Stbd shaft propeller pitch	-	100% of design pitch
Port shaft propeller pitch	-	99% of design pitch

During the conduct of this top spot, the maximum performance was limited by the shaft speed which exceeded its maximum value of 180.0 r/min. The total torque achieved during this top spot was 14.0% below the maximum design torque of 68,800 ft-lbf (93,200 N-m). Figure 3 shows the shaft torque versus shaft speed relationship for the data collected during the Standardization Trial.

Fourteen powering spots were taken to determine the standardization curves in Fig. 2. Three nominal propeller pitch settings were used during the Standardization Trial. These settings were: 100% (design pitch), 120% (maximum ahead pitch), and 90% (under design pitch). Six spots were recorded at the 100% propeller pitch setting, four spots were recorded using 120% pitch, and four spots were recorded using 90% pitch. More runs were done at the nominal 100% pitch setting since it was felt that the standardization curves at design pitch were the most important to define. At the speeds which were run, all above 7 kn, the 100% pitch standardization curves approximate the curves which would be found if the pitch control system had been set in the program control mode. The program control mode theoretically sets the pitch at 100% when the total shaft power reaches 10% of full scale and holds it there. This total shaft power corresponds to a ship speed of approximately 7 kn.

It can be seen in Tables 4 and 5 that for the runs conducted at nominal 120% pitch, the pitch on the starboard shaft was slightly lower at 117%. The method for achieving this pitch setting was different from the method for achieving the 90% and 100% settings and is described in Appendix D. The reason the starboard pitch is slightly lower may be that after achieving a pressure spike on the hub servo oil pressure gage (indicating maximum ahead pitch) the pressure may have been backed off too much dropping the pitch 3%. The pressure is backed off to prevent unnecessary strain on the pitch control rod.

In Figs. 2 and 3, it appears that at 120% of design pitch the AVENGER would achieve maximum torque at a shaft speed of approximately 167 r/min, which would correspond to a ship speed of approximately 14.1 kn. This data point had to be extrapolated from the curves in Figs. 2 and 3 because the port shaft 1645 system recorded a false maximum torque reading at 120% pitch. Since it was not determined that this reading was in error until after the trials, it was thought that maximum torque data had been collected at 120% pitch. This false maximum torque reading also occurred during the locked and trailed shaft trials.

All of the above standardization runs were made with two engines driving each propeller shaft. In addition to these runs, one three run spot was recorded using only one engine driving per shaft. For this spot, the propeller pitch control system was set in the program control mode so that the ship could get the maximum horsepower output from each driving engine. The performance achieved during this one engine per shaft maximum power spot was:

Ship speed by range	-	11.54 kn
Average shaft speed	-	181.5 r/min
Total shaft torque	-	32,400 ft-lbf (44,000 N-m)
Total shaft power	-	1,120 hp (830 kW)
Stbd shaft propeller pitch	-	73% of design
Port shaft propeller pitch	-	75% of design

During the performance of this spot the maximum performance was limited by the shaft speed which exceeded its maximum value of 180.0 r/min. This spot is denoted in Figs. 2 and 3 by an unfilled circle.

Another three run spot was recorded using only the light load propulsion motors. The propeller pitch control system was again set in the program control mode for these runs. The performance achieved with the light load motors at maximum output was:

Ship speed by range	-	7.16 kn
Average shaft speed	-	95.2 r/min
Total shaft torque	-	13,000 ft-lbf (17,600 N-m)
Total shaft power	-	240 hp (180 kW)
Stbd shaft propeller pitch	-	90% of design
Port shaft propeller pitch	-	89% of design

This spot is denoted in Figs. 2 and 3 by an unfilled triangle. Since the pitch used during this spot was nominally 90% of design, this spot was used to extend the 90% standardization curve to the low speed region.

The curves in Figs. 2 and 3 are believed to be accurate representations of AVENGER's speed/powering characteristics in that there were no casualties or restrictions to the power plant.

LOCKED SHAFT TRIAL

The Locked Shaft Trial on AVENGER was conducted on 22 June 1989 at a displacement of 1280 tons (1301 t) and a trim of 1.66 ft (0.51 m) down by the stern. During this trial the port shaft was used to drive the ship, while the starboard shaft was locked in position. The propeller pitch on the driving port shaft was set at 100% (design) pitch, and the locked shaft propeller pitch was set at 15% to minimize the torque on the shaft due to the force produced by the water pushing on the propeller blades. Four data spots were collected throughout the speed range with two engines driving the port shaft. In addition, one spot was performed with only one engine driving the port shaft. The choices for the port shaft to be driving and the starboard shaft to be locked were made so that data from this trial could be correlated with data taken during the Fuel Performance Trials conducted 29 through 31 March

1988. This correlation is discussed in a report of higher classification.*

The results of the Locked Shaft Trial are shown in Fig. 4 and Tables 6 and 7. Figure 4 shows range data collected between 3.97 kn and 9.13 kn. The maximum performance achieved with the starboard shaft locked was:

Ship speed by range	-	9.13 kn
Driving shaft speed	-	167.2 r/min
Driving shaft torque	-	30,400 ft-lbf (41,200 N-m)
Driving shaft power	-	970 hp (720 kW)
Stbd shaft propeller pitch	-	15% of design
Port shaft propeller pitch	-	100% of design

As seen above the actual torque on the port shaft during this spot was 4,000 ft-lbf (5,400 N-m) below the maximum design torque. Maximum torque was not achieved because of the false readings from the port 1645 system discussed earlier in the standardization section.

As mentioned above, one spot was performed with only one engine driving the port shaft. This spot was limited by the shaft speed which exceeded its maximum design speed by 0.3 r/min. For this spot the propeller pitch control system was set in the program control mode so that maximum engine output could be achieved. This switch to program control mode resulted in a propeller pitch of 70% on the driving shaft. This spot is designated by an open circle in Fig. 4.

TRAILED SHAFT TRIAL

The Trailed Shaft Trial on AVENGER was conducted on 22 June 1989 at a displacement of 1280 tons (1301 t) and a trim of 1.66 ft (0.51 m) down by the stern. During this trial the port shaft was again used to drive the ship, while the starboard shaft was trailed allowing it to free wheel. The propeller pitch on the driving port shaft was set at 100% (design) pitch, and the trailing shaft propeller pitch was set at 110% so that it could free wheel

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* Boboltz, David A., Jr., David Taylor Research Center, as reported in a document of higher classification.

easily. Four data spots were collected throughout the speed range with two engines driving the port shaft. In addition, one spot was performed with only one engine driving the port shaft. The choices for the port shaft to be driving and the starboard shaft to be trailing were again made so that data from this trial could be correlated with data taken during the Fuel Performance Trials conducted 29 through 31 March 1988.

The results of the Trailed Shaft Trial are shown in Fig. 4 and Tables 5 and 6. Figure 4 shows range data collected between 3.94 kn and 10.34 kn. The maximum performance achieved with the starboard shaft trailing was:

Ship speed by range	-	10.34 kn
Driving shaft speed	-	168.5 r/min
Driving shaft torque	-	30,300 ft-lbf (41,100 N-m)
Driving shaft power	-	980 hp (730 kW)
Stbd shaft propeller pitch	-	110% of design
Port shaft propeller pitch	-	100% of design

As seen above, the actual torque on the port shaft during this spot was 4,100 ft-lbf (5,500 N-m) below the maximum design torque. Maximum torque was not achieved again because of the false readings from the port 1645 system.

As mentioned above, one spot was performed with one engine driving the port shaft. For this spot the propeller pitch control system was again set in the program control mode so that maximum engine output could be achieved. This switch resulted in a propeller pitch of 77% on the driving shaft. This spot is shown as an open square in Fig. 4.

CONCLUSIONS

Several conclusions may be drawn from the data collected during the Standardization, Locked Shaft, and Trailed Shaft Trials on AVENGER.

1. At design propeller pitch and maximum shaft speed (180 r/min), the AVENGER does not achieve maximum total torque of 68,800 ft-lbf (93,200 N-m).

2. For AVENGER to achieve its maximum torque at a shaft speed of 180 r/min the pitch would have to be raised to approximately 110% of design. This would correspond to a ship speed of approximately 14.4 kn.
3. At any speed above approximately 4.5 kn, it takes a higher shaft torque and a higher shaft speed to achieve a selected ship speed with one shaft locked than it takes to achieve the same speed with the same shaft trailing. Below approximately 4.5 kn, this condition reverses with the trailing shaft mode requiring slightly more shaft torque and shaft speed than the locked shaft mode.

RECOMMENDATIONS

1. Power, torque, and shaft speed data obtained during the AVENGER First of Class Performance Trials indicate that the propeller pitch must be approximately 10% higher than the design pitch to achieve design shaft power at 180 r/min. Only by increasing propeller pitch will the ship reach its maximum attainable speed. It is therefore recommended that the propulsion control system on AVENGER be modified such that 110% propeller pitch is commanded at a shaft speed of 180 r/min.
2. Since the ship's propeller pitch indicating system is subject to error due to variations in hydraulic oil temperature, ambient sea water temperature, and shaft thrust compression, it is important that the ship have reliable and accurate permanent torsionmeters. Accurate torque readouts in the ship's Central Control Station (CCS) are considered essential if the system adjustments recommended above are to be made on AVENGER and other ships of the MCM 1 Class. An accurate knowledge of shaft torque would enable each ship to avoid an over-torque condition resulting from: (1) operations near full power, (2) increases in shaft torque during towing operations, or (3) increases in ship resistance resulting from hull fouling.
3. If for some reason only one shaft is available to drive the ship, the nondriving shaft should be trailed if ship speeds above 4.5 kn are

required. At speeds below 4.5 kn, it is recommended that the nondriving shaft be locked.

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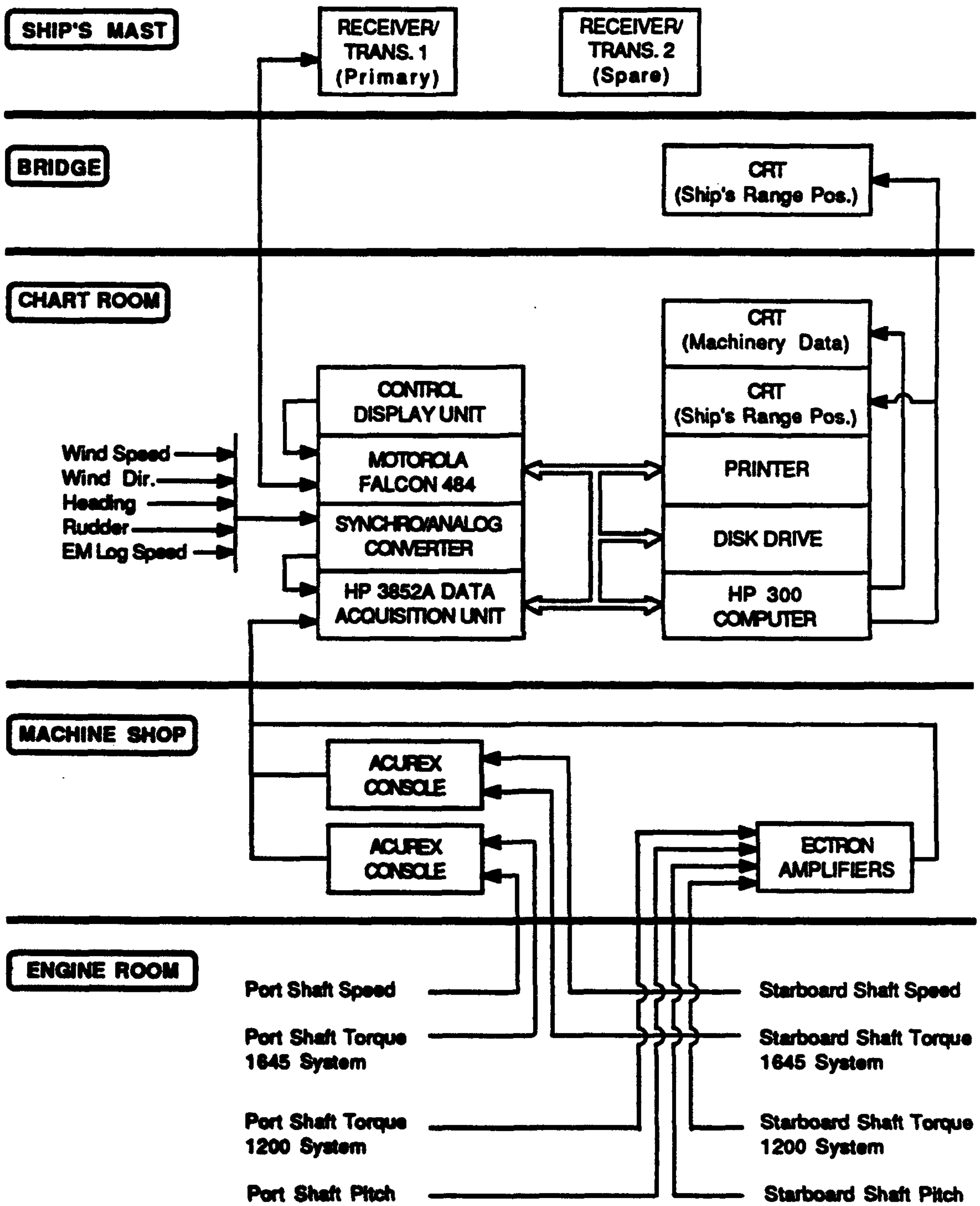

Fig. 1. USS AVENGER (MCM 1) instrumentation block diagram.

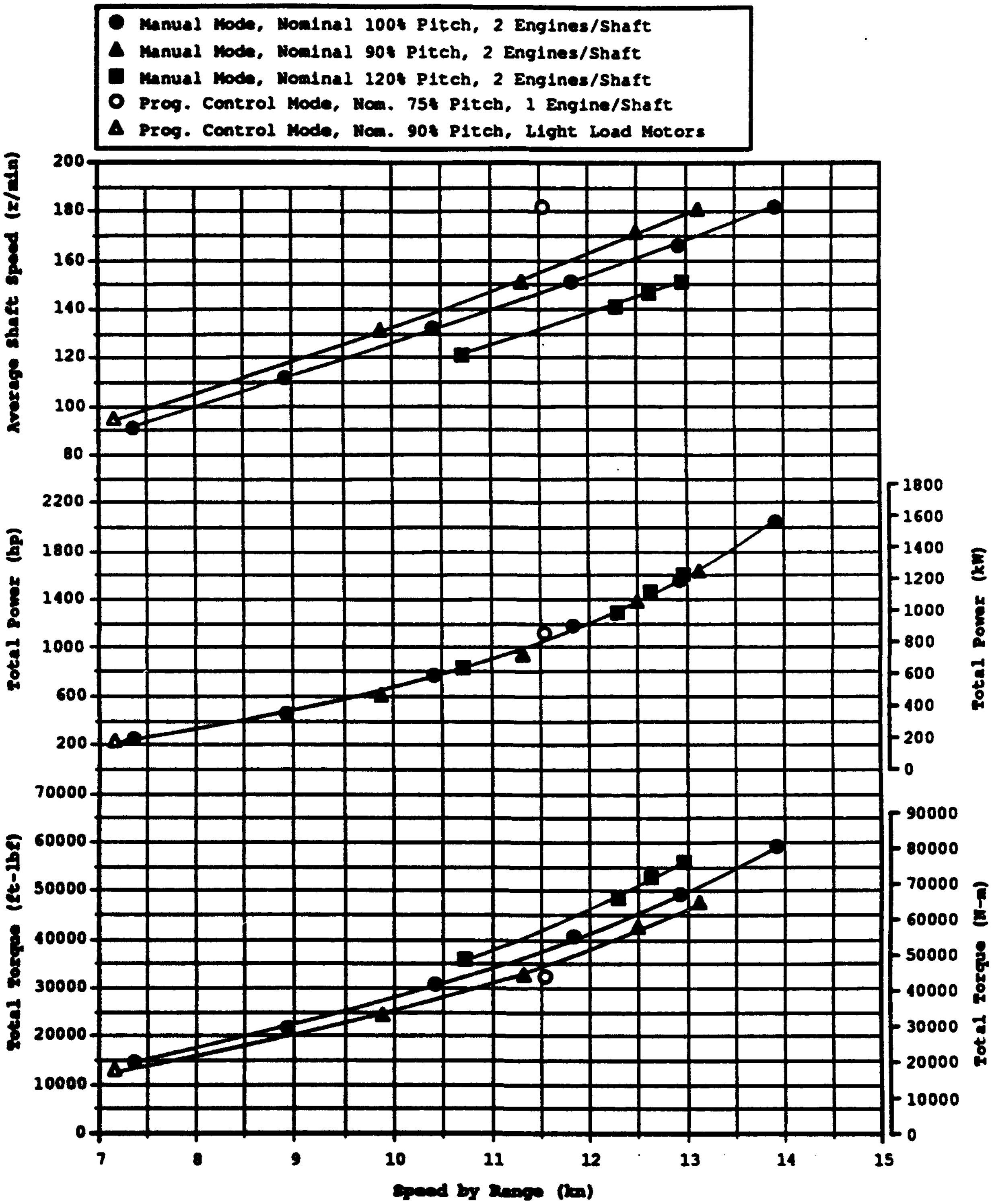

Fig. 2. USS AVENGER (MCM 1) Standardization Trial results.

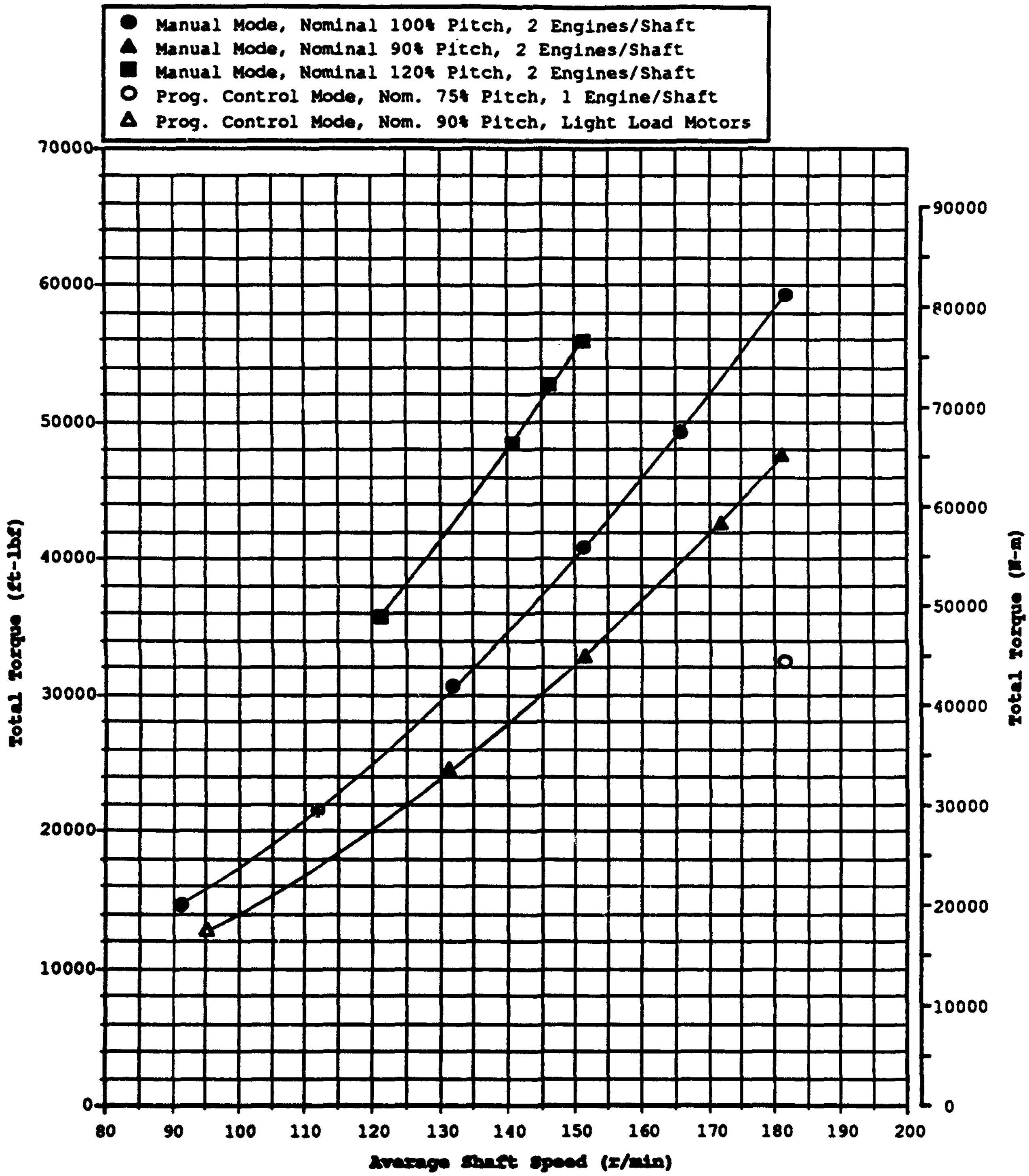

Fig. 3. USS AVENGER (MCM 1) total torque versus average shaft speed.

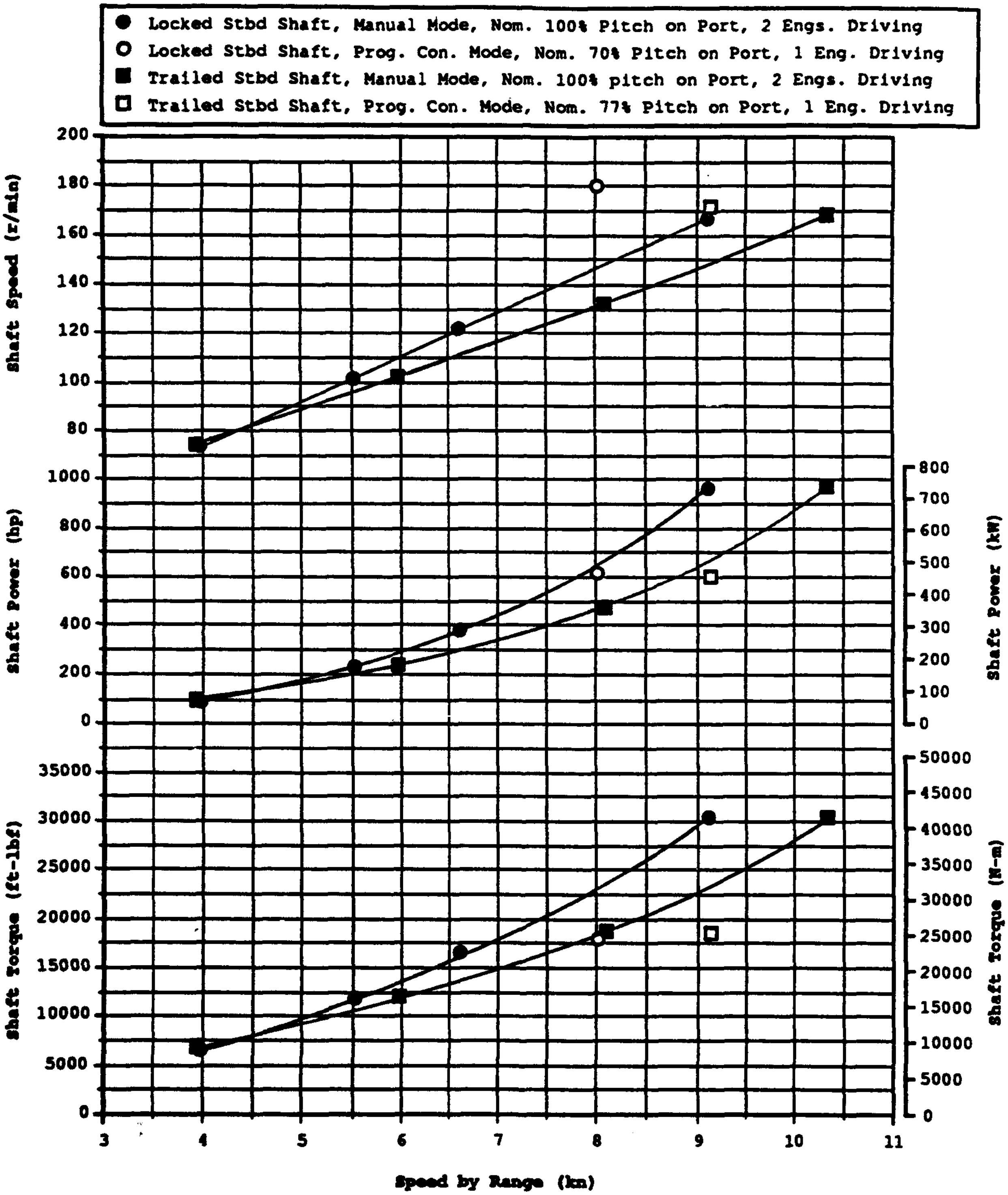

Fig. 4. USS AVENGER (MCM 1) Locked and Trailed Shaft Trial results.

Table 1. USS AVENGER (MCM 1) principal ship and propeller characteristics.

Ship Characteristics	
Length overall (LOA)	224.00 ft (68.275 m)
Length between perpendiculars (LBP)	205.50 ft (62.636 m)
Beam, maximum at DWL	33.60 ft (10.241 m)
Propeller Characteristics	
Number of propellers	2
Serial number (port)	0381
Serial number (starboard)	0382
Type of propeller	CRP
Number of blades	5
Propeller diameter	7.00 ft (2.134 m)
Propeller pitch at 0.7 radius	12.43 ft (3.789 m)
Pitch ratio at 0.7 radius	1.780
Expanded area	29.03 ft^2 (2.697 m^2)
Disc area	38.48 ft^2 (3.575 m^2)
Projected area	22.70 ft^2 (2.109 m^2)
Projected area/disc area	0.590
Total weight of hub with blades (dry)	4553.4 lb (2065.4 kg)
Oil weight to fill hub	120.0 lb (54.4 kg)
Total weight (wet) less buoyancy	3941.4 lb (1787.8 kg)
Material	Ni-Al Bronze
Manufacturer	Bird-Johnson Company
NAVSEA drawing number	5844409

Table 2. USS AVENGER (MCM 1) trial conditions.

Standardization Trial	
Trial date	6/19/89 to 6/20/89
Displacement	1288 tons (1309 t)
Ship trim by the stern	1.33 ft (0.41 m)
Sea state	0-1
Water temperature	81°F (27°C)
Water specific gravity as read	1.025
Air temperature	83-87°F (28-31°C)
True wind speed	8.3-20.8 kn
True wind direction	42°-126°
Locked Shaft and Trailed Shaft Trials	
Trial date	6/22/89
Displacement	1280 tons (1301 t)
Ship trim by the stern	1.66 ft (0.51 m)
Sea state	0-1
Water temperature	81°F (27°C)
Water specific gravity as read	1.025
Air temperature	78-82°F (26-28°C)
True wind speed	7.9-20.4 kn
True wind direction	69°-148°

Table 3. USS AVENGER (MCM 1) measurement accuracies.

Measurement	Source	Calibration Source	Resolution *	Accuracy
Steady Ship Speed	Pulse-Radar System	Surveyed Baseline	0.01 kn	±0.05 kn
Instantaneous Ship Speed	Pulse-Radar System	Surveyed Baseline	0.2 kn	±0.5 kn
Shaft Torque 1645 System	Deflection Sensor	Deflection Calibration Stand	0.02% FS **	±1.5% FS
Shaft Torque 1200 System	Bonded Strain Gage	Shunt Resistor	0.02% FS	±3% FS
Shaft Speed	Infrared Light Sensor	Electronic Oscillator	0.1 r/min	±0.5 r/min
Wind Speed	Anemometer (DC Generator)	Wind Tunnel	0.1 kn	±0.5 kn
Wind Direction	Anemometer (Synchro Transmitter)	Visual Alignment	0.1°	±1° (±5° Alignment)
Rudder Angle	Synchro Transmitter	Rudder Quadrant	0.1°	±0.25°
Ship Heading	Gyrocompass	Gyrocompass	0.1°	±0.25°
Steady EM Log Speed	Synchro Transmitter	Standardization Trials	0.05 kn	±0.25 kn †
Propeller Pitch	Shaped Potentiometer	Diver Measurements	1% of Design	±2% of Design

* Resolution = least detectable change in measurement.
** FS = Full scale.
† When calibrated.

Table 4. USS AVENGER (MCM 1) Standardization Trial results (English units).

Run No.	Range Speed (kn)	EM Log Speed (kn)	Stbd Shaft Spd (r/min)	Port Shaft Spd (r/min)	Stbd Torque 1645 System (ft-lbf)	Port Torque 1200 System (ft-lbf)	Stbd Power (hp)	Port Power (hp)	Stbd Pitch (% des)	Port Pitch (% des)	Average Shaft Spd (r/min)	Total Torque (ft-lbf)	Total Power (hp)	True Wind Spd (kn)	True Wind Dir (deg)
Standardization, Manual Mode, Nominal 100% Pitch, 19 June 1989															
1040S	6.82	8.0	91.6	91.3	7,600	7,500	130	130	99	101	91.5	15,100	260	17.6	100
1050N	7.92	7.6	91.5	91.3	7,100	7,200	120	130	99	100	91.4	14,300	250	15.0	124
1060S	6.76	8.0	91.5	91.3	7,400	7,300	130	130	99	100	91.4	14,700	260	16.0	92
ave	7.36	7.8	91.5	91.3	7,300	7,300	130	130	99	100	91.4	14,600	260		
1070S	8.25	9.5	112.0	111.7	11,000	10,700	230	230	99	99	111.9	21,700	460	17.1	112
1080N	9.65	9.2	112.0	111.6	10,400	10,600	220	230	99	99	111.8	21,000	450	19.6	126
1090S	8.21	9.6	112.0	111.6	11,300	10,900	240	230	99	100	111.8	22,200	470	19.2	115
ave	8.94	9.4	112.0	111.6	10,800	10,700	230	230	99	100	111.8	21,500	460		
1100N	11.07	10.6	132.1	132.1	14,900	15,000	370	380	100	100	132.1	29,900	750	19.4	123
1110S	9.74	11.1	131.9	132.1	16,100	15,100	400	380	101	100	132.0	31,200	780	18.9	114
1120N	11.16	10.7	131.7	131.9	15,500	15,000	390	380	101	100	131.8	30,500	770	20.8	125
ave	10.43	10.9	131.9	132.1	15,700	15,100	390	380	101	100	132.0	30,700	770		
1130N	12.34	12.0	151.1	151.6	20,900	20,000	600	580	101	100	151.4	40,900	1,180	13.5	91
1140S	11.36	12.6	151.0	151.6	21,200	19,700	610	570	101	100	151.3	40,900	1,180	18.5	105
1150N	12.30	12.0	151.0	151.6	20,700	19,800	600	570	101	100	151.3	40,500	1,170	15.6	101
ave	11.84	12.3	151.0	151.6	21,000	19,800	610	570	101	100	151.3	40,800	1,180		
1160S	12.53	13.7	165.0	166.7	25,400	23,800	800	760	101	99	165.9	49,200	1,560	13.8	92
1170N	13.37	13.1	165.0	166.7	25,300	24,000	790	760	101	98	165.9	49,300	1,550	15.9	101
1180S	12.44	13.7	165.0	166.6	25,400	23,900	800	760	101	98	165.8	49,300	1,560	15.3	91
ave	12.93	13.4	165.0	166.7	25,400	23,900	800	760	101	98	165.9	49,300	1,560		
1190S	13.33	14.5	181.6	181.8	30,700	28,600	1,060	990	101	98	181.7	59,300	2,050	19.9	111
1200N	14.69	14.2	181.7	181.9	29,900	29,200	1,030	1,010	101	99	181.8	59,100	2,040	15.6	109
1210S	12.98	14.6	181.4	181.8	30,300	29,300	1,050	1,010	100	99	181.6	59,600	2,060	19.1	118
ave	13.92	14.4	181.6	181.9	30,200	29,100	1,040	1,010	100	99	181.7	59,300	2,050		
Standardization, Program Control Mode, One Engine Per Shaft, 19 June 1989															
1175S	11.19	12.3	181.2	181.6	15,700	17,200	540	590	74	76	181.4	32,900	1,130	18.0	113
1176N	11.94	11.7	181.1	181.8	15,300	16,800	530	580	73	75	181.5	32,100	1,110	15.2	104
1177S	11.10	12.2	181.1	181.6	15,700	16,800	540	580	73	75	181.4	32,500	1,120	18.6	117
ave	11.54	12.0	181.1	181.7	15,500	16,900	540	580	73	75	181.5	32,400	1,120		
Standardization, Program Control Mode, Light Load Motors, 19 June 1989															
3010N	7.57	7.5	94.8	94.2	6,100	6,500	110	120	90	89	94.5	12,600	230	18.1	118
3020S	6.70	7.9	95.6	95.0	6,500	6,600	120	120	90	89	95.3	13,100	240	12.4	98
3030N	7.65	7.4	96.2	95.4	6,400	6,700	120	120	89	88	95.8	13,100	240	13.8	103
ave	7.16	7.7	95.6	94.9	6,400	6,600	120	120	90	89	95.2	13,000	240		

Table 4. (Continued)

Run No.	Range Speed (kn)	EM Log Speed (kn)	Stbd Shaft Spd (r/min)	Port Shaft Spd (r/min)	Stbd Torque 1645 System (ft-lbf)	Port Torque 1200 System (ft-lbf)	Stbd Power (hp)	Port Power (hp)	Stbd Pitch (% des)	Port Pitch (% des)	Average Shaft Spd (r/min)	Total Torque (ft-lbf)	Total Power (hp)	True Wind Spd (kn)	True Wind Dir (deg)
Standardization, Manual Mode, Nominal 120% Pitch, 20 June 1989															
2810S	10.22	11.5	121.0	121.7	17,400	18,100	400	420	117	120	121.4	35,500	820	14.5	68
2820N	11.21	10.7	121.0	121.8	17,600	18,500	410	430	118	120	121.4	36,100	840	11.9	69
2830S	10.27	11.5	121.0	121.8	17,300	18,100	400	420	118	120	121.4	35,400	820	10.4	62
ave	10.73	11.1	121.0	121.8	17,500	18,300	410	430	117	120	121.4	35,800	830		
2840S	11.58	12.9	140.5	141.3	23,800	24,700	640	660	117	120	140.9	48,500	1,300	11.7	86
2850N	13.02	12.4	140.6	141.2	23,600	24,800	630	670	117	120	140.9	48,400	1,300	11.1	96
2860S	11.56	12.8	140.6	141.3	23,600	24,700	630	660	117	120	141.0	48,300	1,290	12.2	76
ave	12.30	12.6	140.6	141.3	23,700	24,800	630	670	117	120	140.9	48,400	1,300		
2900S	12.09	13.2	145.0	146.7	24,900	26,700	690	750	117	120	145.9	51,600	1,440	14.2	43
2910N	13.22*	12.6	146.1	146.8	25,500	27,800	710	780	116	120	146.5	53,300	1,490	16.7	49
2920S	12.08	13.3	146.2	146.8	25,200	27,200	700	760	116	120	146.5	52,400	1,460	16.7	42
ave	12.63	12.9	145.9	146.8	25,300	27,400	700	770	117	120	146.4	52,700	1,470		
2870N	13.42	13.0	151.1	151.3	27,500	28,900	790	830	117	120	151.2	56,400	1,620	14.9	80
2880S	12.47	13.6	151.1	151.3	27,100	28,400	780	820	117	120	151.2	55,500	1,600	11.3	67
2890N	13.52	13.2	151.0	151.3	27,200	28,800	780	830	117	120	151.2	56,000	1,610	9.6	63
ave	12.97	13.4	151.1	151.3	27,200	28,600	780	830	117	120	151.2	55,900	1,610		
Standardization, Manual Mode, Nominal 90% Pitch, 20 June 1989															
2000N	10.33	9.8	130.9	131.7	12,200	12,700	300	320	90	90	131.3	24,900	620	13.8	70
2010S	9.38	10.6	130.9	131.7	12,000	12,400	300	310	90	90	131.3	24,400	610	12.5	91
2020N	10.48	10.0	130.9	131.8	12,100	12,600	300	320	90	91	131.4	24,700	620	11.7	80
ave	9.89	10.3	130.9	131.7	12,100	12,500	300	320	90	90	131.3	24,600	620		
2030S	10.66	11.9	151.4	151.3	16,500	16,300	480	470	90	91	151.4	32,800	950	8.3	98
2040N	11.80	11.4	151.3	151.3	16,500	16,600	480	480	90	91	151.3	33,100	960	12.0	75
2050S	10.98	12.0	151.3	151.4	16,200	16,200	470	470	90	90	151.4	32,400	940	13.5	57
ave	11.31	11.7	151.3	151.3	16,400	16,400	480	480	90	91	151.4	32,900	950		
2060S	12.16	13.3	171.8	171.8	21,600	21,200	710	690	90	90	171.8	42,800	1,400	14.1	102
2070N	12.83	12.8	171.9	171.8	21,300	21,200	700	690	90	89	171.9	42,500	1,390	15.3	110
2080S	12.13	13.2	171.9	171.8	21,500	21,100	700	690	90	89	171.9	42,600	1,390	13.4	104
ave	12.49	13.0	171.9	171.8	21,400	21,200	700	690	90	89	171.9	42,600	1,390		
2090S	12.75	13.8	181.4	181.4	23,900	23,400	830	810	89	89	181.4	47,300	1,640	13.9	105
2100N	13.50	13.4	181.0	181.2	24,900	23,300	860	800	89	88	181.1	48,200	1,660	11.7	98
2110S	12.77	13.8	179.9	181.3	23,500	23,000	800	790	89	88	180.6	46,500	1,590	10.7	88
ave	13.13	13.6	180.8	181.3	24,300	23,300	840	800	89	88	181.1	47,600	1,640		

* Speed data not available. Speed was interpolated from northward runs occurring before and afterwards.

Table 5. USS AVENGER (MCM 1) Standardization Trial results (metric units).

Run No.	Range Speed (kn)	EM Log Speed (kn)	Stbd Shaft Spd (r/min)	Port Shaft Spd (r/min)	Stbd Torque 1645 System (N-m)	Port Torque 1200 System (N-m)	Stbd Power (kW)	Port Power (kW)	Stbd Pitch (% des)	Port Pitch (% des)	Average Shaft Spd (r/min)	Total Torque (N-m)	Total Power (kW)	True Wind Spd (kn)	True Wind Dir (deg)
Standardization, Manual Mode, Nominal 100% Pitch, 19 June 1989															
1040S	6.82	8.0	91.6	91.3	10,300	10,200	100	100	99	101	91.5	20,500	200	17.6	100
1050N	7.92	7.6	91.5	91.3	9,600	9,800	90	90	99	100	91.4	19,400	180	15.0	124
1060S	6.76	8.0	91.5	91.3	10,100	9,900	100	90	99	100	91.4	20,000	190	16.0	92
ave	7.36	7.8	91.5	91.3	9,900	9,900	100	90	99	100	91.4	19,800	190		
1070S	8.25	9.5	112.0	111.7	14,900	14,500	170	170	99	99	111.9	29,400	340	17.1	112
1080N	9.65	9.2	112.0	111.6	14,200	14,400	170	170	99	99	111.8	28,600	340	19.6	126
1090S	8.21	9.6	112.0	111.6	15,300	14,800	180	170	99	100	111.8	30,100	350	19.2	115
ave	8.94	9.4	112.0	111.6	14,700	14,500	170	170	99	100	111.8	29,200	340		
1100N	11.07	10.6	132.1	132.1	20,200	20,300	280	280	100	100	132.1	40,500	560	19.4	123
1110S	9.74	11.1	131.9	132.1	21,800	20,400	300	280	101	100	132.0	42,200	580	18.9	114
1120N	11.16	10.7	131.7	131.9	21,000	20,300	290	280	101	100	131.8	41,300	570	20.8	125
ave	10.43	10.9	131.9	132.1	21,200	20,400	290	280	101	100	132.0	41,600	570		
1130N	12.34	12.0	151.1	151.6	28,300	27,200	450	430	101	100	151.4	55,500	880	13.5	91
1140S	11.36	12.6	151.0	151.6	28,700	26,800	450	430	101	100	151.3	55,500	880	18.5	105
1150N	12.30	12.0	151.0	151.6	28,100	26,900	440	430	101	100	151.3	55,000	870	15.6	101
ave	11.84	12.3	151.0	151.6	28,500	26,900	450	430	101	100	151.3	55,400	880		
1160S	12.53	13.7	165.0	166.7	34,500	32,300	600	560	101	99	165.9	66,800	1,160	13.8	92
1170N	13.37	13.1	165.0	166.7	34,300	32,500	590	570	101	98	165.9	66,800	1,160	15.9	101
1180S	12.44	13.7	165.0	166.6	34,500	32,400	600	570	101	98	165.8	66,900	1,170	15.3	91
ave	12.93	13.4	165.0	166.7	34,400	32,400	600	570	101	98	165.9	66,800	1,160		
1190S	13.33	14.5	181.6	181.8	41,700	38,700	790	740	101	98	181.7	80,400	1,530	19.9	111
1200N	14.69	14.2	181.7	181.9	40,500	39,500	770	750	101	99	181.8	80,000	1,520	15.6	109
1210S	12.98	14.6	181.4	181.8	41,100	39,700	780	760	100	99	181.6	80,800	1,540	19.1	118
ave	13.92	14.4	181.6	181.9	41,000	39,400	780	750	100	99	181.7	80,300	1,530		
Standardization, Program Control Mode, One Engine Per Shaft, 19 June 1989															
1175S	11.19	12.3	181.2	181.6	21,300	23,400	400	450	74	76	181.4	44,700	850	18.0	113
1176N	11.94	11.7	181.1	181.8	20,800	22,800	390	430	73	75	181.5	43,600	820	15.2	104
1177S	11.10	12.2	181.1	181.6	21,200	22,800	400	430	73	75	181.4	44,000	830	18.6	117
ave	11.54	12.0	181.1	181.7	21,000	23,000	400	440	73	75	181.5	44,000	830		
Standardization, Program Control Mode, Light Load Motors, 19 June 1989															
3010N	7.57	7.5	94.8	94.2	8,300	8,900	80	90	90	89	94.5	17,200	170	18.1	118
3020S	6.70	7.9	95.6	95.0	8,800	8,900	90	90	90	89	95.3	17,700	180	12.4	98
3030N	7.65	7.4	96.2	95.4	8,700	9,100	90	90	89	88	95.8	17,800	180	13.8	103
ave	7.16	7.7	95.6	94.9	8,700	9,000	90	90	90	89	95.2	17,600	180		

Table 5. (Continued)

Run No.	Range Speed (kn)	EM Log Speed (kn)	Stbd Shaft Spd (r/min)	Port Shaft Spd (r/min)	Stbd Torque 1645 System (N-m)	Port Torque 1200 System (N-m)	Stbd Power (kW)	Port Power (kW)	Stbd Pitch (% design)	Port Pitch (% design)	Average Shaft Spd (r/min)	Total Torque (N-m)	Total Power (kW)	True Wind Spd (kn)	True Wind Dir (deg)
Standardization, Manual Mode, Nominal 120% Pitch, 20 June 1989															
2810S	10.22	11.5	121.0	121.7	23,700	24,600	300	310	117	120	121.4	48,300	610	14.5	68
2820N	11.21	10.7	121.0	121.8	24,000	25,100	300	320	118	120	121.4	49,100	620	11.9	69
2830S	10.27	11.5	121.0	121.8	23,700	24,600	300	310	118	120	121.4	48,300	610	10.4	62
ave	10.73	11.1	121.0	121.8	23,900	24,900	300	320	117	120	121.4	48,700	620		
2840S	11.58	12.9	140.5	141.3	32,400	33,400	480	490	117	120	140.9	65,800	970	11.7	86
2850N	13.82	12.4	140.6	141.2	32,200	33,600	470	500	117	120	140.9	65,800	970	11.1	96
2860S	11.56	12.8	140.6	141.3	32,100	33,500	470	500	117	120	141.0	65,600	970	12.2	76
ave	12.30	12.6	140.6	141.3	32,200	33,500	470	500	117	120	140.9	65,800	970		
2900S	12.09	13.2	145.0	146.7	34,000	36,100	520	550	117	120	145.9	70,100	1,070	14.2	43
2910N	13.22*	12.6	146.1	146.8	34,800	37,700	530	580	116	120	146.5	72,500	1,110	16.7	49
2920S	12.00	13.3	146.2	146.8	34,400	36,900	530	570	116	120	146.5	71,300	1,100	16.7	42
ave	12.63	12.9	145.9	146.8	34,500	37,100	530	570	117	120	146.4	71,600	1,100		
2870N	13.42	13.0	151.1	151.3	37,500	39,200	590	620	117	120	151.2	76,700	1,210	14.9	80
2880S	12.47	13.6	151.1	151.3	37,000	38,600	590	610	117	120	151.2	75,600	1,200	11.3	67
2890N	13.52	13.2	151.0	151.3	37,100	39,000	590	620	117	120	151.2	76,100	1,210	9.6	63
ave	12.97	13.4	151.1	151.3	37,200	38,900	590	620	117	120	151.2	76,000	1,210		
Standardization, Manual Mode, Nominal 90% Pitch, 20 June 1989															
2000N	10.33	9.8	130.9	131.7	16,700	17,200	230	240	90	90	131.3	33,900	470	13.8	70
2010S	9.38	10.6	130.9	131.7	16,500	16,800	230	230	90	90	131.3	33,300	460	12.5	91
2020N	10.48	10.8	130.9	131.8	16,500	17,000	230	230	90	91	131.4	33,500	460	11.7	80
ave	9.89	10.3	130.9	131.7	16,600	17,000	230	230	90	90	131.3	33,500	460		
2030S	10.66	11.9	151.4	151.3	22,500	22,100	360	350	90	91	151.4	44,600	710	8.3	98
2040N	11.80	11.4	151.3	151.3	22,600	22,500	360	360	90	91	151.3	45,100	720	12.0	75
2050S	10.98	12.0	151.3	151.4	22,200	21,900	350	350	90	90	151.4	44,100	700	13.5	57
ave	11.31	11.7	151.3	151.3	22,500	22,300	360	360	90	91	151.4	44,700	710		
2060S	12.16	13.3	171.8	171.8	29,600	28,700	530	520	90	90	171.8	58,300	1,050	14.1	102
2070N	12.83	12.8	171.9	171.8	29,000	28,800	520	520	90	89	171.9	57,800	1,040	15.3	110
2080S	12.13	13.2	171.9	171.8	29,300	28,600	530	510	90	89	171.9	57,900	1,040	13.4	104
ave	12.49	13.0	171.9	171.8	29,200	28,700	530	520	90	89	171.9	58,000	1,040		
2090S	12.75	13.8	181.4	181.4	32,600	31,800	620	600	89	89	181.4	64,400	1,220	13.9	105
2100N	13.50	13.4	181.0	181.2	34,000	31,600	640	600	89	88	181.1	65,600	1,240	11.7	98
2110S	12.77	13.8	179.9	181.3	32,000	31,200	600	590	89	88	180.6	63,200	1,190	10.7	88
ave	13.13	13.6	180.8	181.3	33,200	31,600	630	600	89	88	181.1	64,700	1,220		

* Speed data not available. Speed was interpolated from northward runs occurring before and afterwards.

Table 6. USS AVENGER (MCM 1) Locked Shaft Trial results (English units).

Run No.	Range Speed (kn)	EM Log Speed (kn)	Starboard Shaft Spd (r/min)	Port Shaft Spd (r/min)	Stbd Torque 1645 System (ft-lbf)	Port Torque 1200 System (ft-lbf)	Stbd Power (hp)	Port Power (hp)	Starboard Pitch (% design)	Port Pitch (% design)	True Wind Spd (kn)	True Wind Dir (deg)
Locked Shaft, Manual Mode, Nominal 100% Pitch on Driving Port Shaft, Nominal 15% Pitch on Locked Starboard Shaft, 22 June 1989												
2610N	4.18	4.5	0.0	74.0	1,200	6,500	0	90	16	101	8.3	93
2620S	3.75	4.6	0.0	73.9	1,300	6,400	0	90	15	100	8.7	69
ave	3.97	4.6	0.0	74.0	1,300	6,500	0	90	16	101		
2640S	5.52	6.3	0.0	101.9	1,200	11,700	0	230	15	101	7.9	70
2650N	5.70	6.0	0.0	101.6	1,300	12,000	0	230	15	101	15.9	107
2660S	5.18	6.0	0.0	101.7	1,300	11,500	0	220	15	100	18.3	106
ave	5.53	6.1	0.0	101.7	1,300	11,800	0	230	15	100		
2670S	6.39	7.1	0.0	121.6	1,200	16,300	0	380	16	100	17.6	105
2680N	6.81	7.0	0.0	121.6	1,100	16,700	0	390	15	100	17.7	114
2690S	6.48	7.3	0.0	121.6	1,100	16,600	0	380	15	101	16.3	101
ave	6.62	7.1	0.0	121.6	1,100	16,600	0	390	15	100		
2700N	9.37	9.4	0.0	167.2	700	30,400	0	970	15	100	13.0	114
2710S	8.88	9.8	0.0	167.2	700	30,300	0	960	15	100	12.8	106
2720N	9.38	9.5	0.0	167.3	800	30,400	0	970	15	100	14.1	123
ave	9.13	9.6	0.0	167.2	700	30,400	0	970	15	100		
Locked Shaft, Program Control Mode, One Engine Driving Port Shaft, 70% Pitch on Driving Port Shaft, 15% Pitch on Locked Starboard Shaft, 22 June 1989												
2730S	7.81	8.6	0.0	179.6	800	18,000	0	620	15	70	12.2	112
2740N	8.27	8.4	0.0	180.6	800	18,000	0	620	15	70	12.3	129
2750S	7.73	8.6	0.0	180.4	800	18,000	0	620	15	69	13.5	121
ave	8.02	8.5	0.0	180.3	800	18,000	0	620	15	70		

Table 7. USS AVENGER (MCM 1) Locked Shaft Trial results (metric units).

Run No.	Range Speed (kn)	EM Log Speed (kn)	Starboard Shaft Spd (r/min)	Port Shaft Spd (r/min)	Stbd Torque 1645 System (N-m)	Port Torque 1200 System (N-m)	Stbd Power (kW)	Port Power (kW)	Starboard Pitch (% design)	Port Pitch (% design)	True Wind Spd (kn)	True Wind Dir (deg)
Locked Shaft, Manual Mode, Nominal 100% Pitch on Driving Port Shaft, Nominal 15% Pitch on Locked Starboard Shaft, 22 June 1989												
2610N	4.18	4.5	0.0	74.0	1,600	8,800	0	70	16	101	8.3	93
2620S	3.75	4.6	0.0	73.9	1,800	8,700	0	70	15	100	8.7	69
ave	3.97	4.6	0.0	74.0	1,700	8,800	0	70	16	101		
2640S	5.52	6.3	0.0	101.9	1,600	15,900	0	170	15	101	7.9	70
2650N	5.70	6.0	0.0	101.6	1,800	16,300	0	170	15	101	15.9	107
2660S	5.18	6.0	0.0	101.7	1,800	15,600	0	170	15	100	18.3	106
ave	5.53	6.1	0.0	101.7	1,800	16,000	0	170	15	100		
2670S	6.39	7.1	0.0	121.6	1,600	22,100	0	280	16	100	17.6	105
2680N	6.81	7.0	0.0	121.6	1,500	22,600	0	290	15	100	17.7	114
2690S	6.48	7.3	0.0	121.6	1,500	22,500	0	290	15	101	16.3	101
ave	6.62	7.1	0.0	121.6	1,500	22,500	0	290	15	100		
2700N	9.37	9.4	0.0	167.2	900	41,200	0	720	15	100	13.0	114
2710S	8.88	9.8	0.0	167.2	900	41,100	0	720	15	100	12.8	106
2720N	9.38	9.5	0.0	167.3	1,100	41,200	0	720	15	100	14.1	123
ave	9.13	9.6	0.0	167.2	1,000	41,200	0	720	15	100		
Locked Shaft, Program Control Mode, One Engine Driving Port Shaft, 70% Pitch on Driving Port Shaft, 15% Pitch on Locked Starboard Shaft, 22 June 1989												
2730S	7.81	8.6	0.0	179.6	1,100	24,400	0	460	15	70	12.2	112
2740N	8.27	8.4	0.0	180.6	1,100	24,400	0	460	15	70	12.3	129
2750S	7.73	8.6	0.0	180.4	1,100	24,400	0	460	15	69	13.5	121
ave	8.02	8.5	0.0	180.3	1,100	24,400	0	460	15	70		

Table 8. USS AVENGER (MCM 1) Trailed Shaft Trial results (English units).

Run No.	Range Speed (kn)	EM Log Speed (kn)	Starboard Shaft Spd (r/min)	Port Shaft Spd (r/min)	Stbd Torque 1645 System (ft-lbf)	Port Torque 1200 System (ft-lbf)	Stbd Power (hp)	Port Power (hp)	Starboard Pitch (% design)	Port Pitch (% design)	True Wind Spd (kn)	True Wind Dir (deg)
Trailed Shaft, Manual Mode, Nominal 100% Pitch on Driving Port Shaft, Nominal 110% Pitch on Trailing Starboard Shaft, 22 June 1989												
2410S	3.70	4.4	0.0	74.7	700	6,800	0	100	110	102	14.0	117
2420N	4.24	4.7	0.0	74.4	600	7,000	0	100	110	101	13.7	118
2430S	3.56	4.4	0.0	74.5	600	6,800	0	100	111	101	15.9	108
ave	3.94	4.6	0.0	74.5	600	6,900	0	100	110	101		
2440S	5.36	6.1	0.0	102.2	-400	12,400	0	240	111	102	17.2	108
2450N	6.30	6.5	35.1	102.2	-100	12,100	0	240	111	101	15.5	122
2460S	5.94	6.7	34.5	102.2	0	11,900	0	230	110	101	15.8	116
ave	5.98	6.5	26.2	102.2	-200	12,100	0	240	111	101		
2470N	8.38	8.6	55.4	132.0	-100	18,700	0	470	110	102	20.4	120
2480S	7.96	8.8	51.6	132.0	-100	18,800	0	470	110	102	18.2	109
2490N	8.11	8.5	52.5	132.1	-100	18,900	0	480	110	102	17.2	114
ave	8.10	8.7	52.8	132.0	-100	18,800	0	470	110	102		
2500N	10.83	10.9	69.7	171.5	-200	31,500	0	1,030	110	102	18.2	120
2510S	9.97	11.0	68.1	167.4	-100	30,000	0	960	110	102	16.0	108
2520N	10.58	10.8	70.6	167.7	-200	29,700	0	950	111	101	15.6	133
ave	10.34	10.9	69.1	168.5	-200	30,300	0	980	110	102		
Trailed Shaft, Program Control Mode, One Engine Driving Port Shaft, 77% Pitch on Driving Port Shaft, 110% Pitch on Trailed Starboard Shaft, 22 June 1989												
2560S	8.81	9.6	58.6	170.2	-100	18,600	0	600	110	77	11.3	148
2570N	9.48	9.9	62.4	172.5	-100	18,500	0	610	110	77	10.9	148
ave	9.15	9.8	60.5	171.4	-100	18,600	0	610	110	77		

Table 9. USS AVENGER (MCM 1) Trailed Shaft Trial results (metric units).

Run No.	Range Speed (kn)	EM Log Speed (kn)	Starboard Shaft Spd (r/min)	Port Shaft Spd (r/min)	Stbd Torque 1645 System (N-m)	Port Torque 1200 System (N-m)	Stbd Power (kW)	Port Power (kW)	Starboard Pitch (% design)	Port Pitch (% design)	True Wind Spd (kn)	True Wind Dir (deg)
Trailed Shaft, Manual Mode, Nominal 100% Pitch on Driving Port Shaft, Nominal 110% Pitch on Trailing Starboard Shaft, 22 June 1989												
2410S	3.70	4.4	0.0	74.7	900	9,200	0	70	110	102	14.0	117
2420N	4.24	4.7	0.0	74.4	800	9,500	0	70	110	101	13.7	118
2430S	3.56	4.4	0.0	74.5	800	9,200	0	70	111	101	15.9	108
ave	3.94	4.6	0.0	74.5	800	9,400	0	70	110	101		
2440S	5.36	6.1	0.0	102.2	-500	16,800	0	180	111	102	17.2	108
2450N	6.30	6.5	35.1	102.2	-100	16,400	0	180	111	101	15.5	122
2460S	5.94	6.7	34.5	102.2	0	16,100	0	170	110	101	15.8	116
ave	5.98	6.5	26.2	102.2	-200	16,400	0	180	111	101		
2470N	8.38	8.6	55.4	132.0	-100	25,400	0	350	110	102	20.4	120
2480S	7.96	8.8	51.6	132.0	-100	25,500	0	350	110	102	18.2	109
2490N	8.11	8.5	52.5	132.1	-100	25,600	0	350	110	102	17.2	114
ave	8.10	8.7	52.8	132.0	-100	25,500	0	350	110	102		
2500N	10.83	10.9	69.7	171.5	-300	42,700	0	770	110	102	18.2	120
2510S	9.97	11.0	68.1	167.4	-100	40,700	0	710	110	102	16.0	108
2520N	10.58	10.8	70.6	167.7	-300	40,300	0	710	111	101	15.6	133
ave	10.34	10.9	69.1	168.5	-200	41,100	0	730	110	102		
Trailed Shaft, Program Control Mode, One Engine Driving Port Shaft, 77% Pitch on Driving Port Shaft, 110% Pitch on Trailed Starboard Shaft, 22 June 1989												
2560S	8.81	9.6	58.6	170.2	-100	25,200	0	450	110	77	11.3	148
2570N	9.48	9.9	62.4	172.5	-100	25,100	0	450	110	77	10.9	148
ave	9.15	9.8	60.5	171.4	-100	25,200	0	450	110	77		

APPENDIX A

USS AVENGER (MCM 1) SHIP POSITION AND SPEED MEASUREMENTS

The following appendix describes the tracking range used by DTRC and the process by which the position relative to that range is determined. It also describes how the ship speed by range is dervied from the positional information.

DTRC established a tracking site off the west coast of St. Croix, U.S. Virgin Islands. A baseline for the trial site was established between Sprat and Sandy Point. This baseline is 7630.5 yd (6977.3 m) long and defines a base course of 008° and 188°. Since tracking accuracy is related to system geometry, ship trials are normally conducted within a 1 nmi^2 (1.8 km^2) area. The center of this trial site area was located approximately 1.9 nmi perpendicular to the center of the baseline. Water depth in the area where trials were conducted was in excess of 1800 ft (548.6 m). Figure A.1 shows the DTRC tracking range including the location of the two reference stations and the area where trials were conducted.

The primary means of determining ship position was the Motorola Falcon 484 pulse radar positioning system. A transmitter, located on the ship, was used to interrogate four reference station transponders. These transponders were mounted on shore separated by the known baseline distance. The elapsed time between the transmitted interrogation produced by the Falcon transmitter and the reply received from each transponder was used as the basis for determining the distance to each transponder. This range information, together with the known location of each transponder, was used to provide a positional fix on the ship. Successive positional fixes enabled the calculation of ship speed as well as its turning and maneuvering capabilities.

The approach for each trial run was generally conducted near the center of the tracking range on a course parallel to the base course determined by the two reference stations. During trials, a heading of 008° was used for north runs and a heading of 188° was used for south runs. This baseline course will be called the x-axis of the range. The y-axis is perpendicular to this baseline course. During the runs, the Falcon system recorded positional fixes which were converted to x and y coordinates of the ship on the range. From these positional fixes and the time between the fixes, the x and y components of ship speed were determined. Since only the x component of the speed is desired, the y component was not used.

Part of the above x component of speed is due to currents in the trial area. To eliminate this component due to current, a mean of means averaging technique was used. For a three pass spot, the data for the odd direction were weighted twice and the four runs were then averaged. Mean of means averaging for a three pass spot assumes that the current varies linearly over time. For a two pass spot, the mean of means averaging weights each pass equally and averages the two. When only two passes were run for a spot, the mean of means average assumes that the current is a constant in time. This situation is acceptable if the runs are closely spaced in time.

The speeds by range reported previously in this report are the x components of the speed discussed above with the speed due to current eliminated. For Standardization, Locked Shaft, and Trailed Shaft Trials the reported speeds by range are accurate to within +/- 0.05 kn.

The average baseline trial speed for each test spot was compared to the ship's EM log speed. It can be seen in Fig. A.2 that the EM log generally indicated a ship speed approximately 0.5 kn higher than the Falcon system indicated during the performance of Standardization, Locked Shaft, and Trailed Shaft Trials.

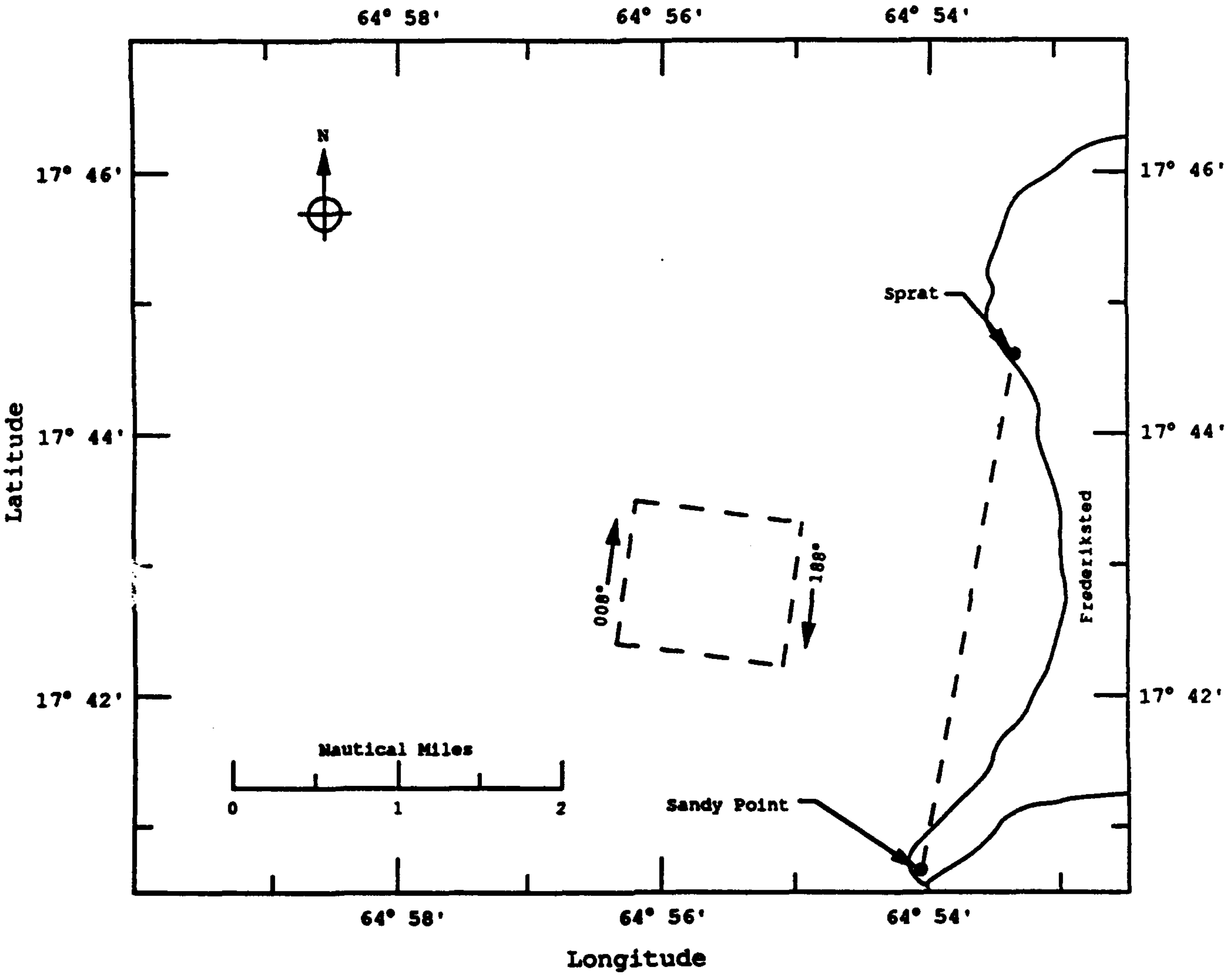

Fig. A.1. Tracking range, St. Croix, U.S. Virgin Islands.

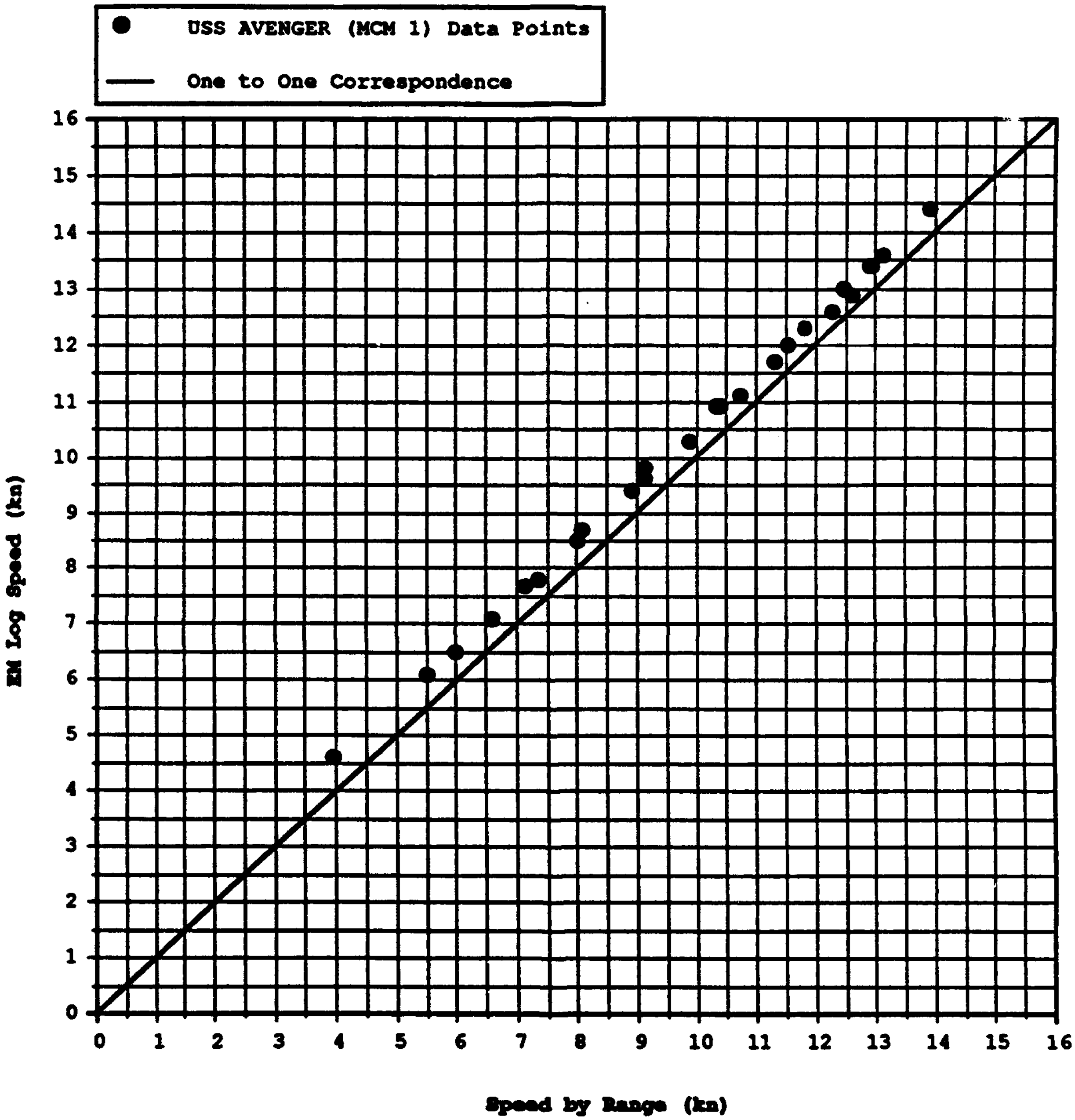

Fig. A.2. USS AVENGER (MCM 1) speed by range versus EM log speed.

APPENDIX B

USS AVENGER (MCM 1) DISPLACEMENT CALCULATIONS

The following discussion explains the process for determining the displacement of AVENGER during the Standardization, Locked Shaft, and Trailed Shaft Trials.

The displacement was calculated based on the visual draft readings taken prior to getting underway and upon arrival at the Frederiksted Pier, St. Croix, U.S. Virgin Islands. These morning and evening sets of draft readings were averaged to get daily drafts for each day of the trials on AVENGER. The specific gravity and temperature of the water were also needed to complete the displacement calculations. These measurements were taken at both the pier and at sea each day, but, due to the proximity of the pier to the open ocean, the readings were the same at both locations. These readings also remained constant from day to day at 1.025 for specific gravity and 81°F for water temperature. Since the hydrometer used to measure the specific gravity was calibrated so that the specific gravity of fresh water at 60°F is 1.000, the measured value of 1.025 had to be corrected for the temperature difference of 21°F. This corrected specific gravity is given in Tables B.1 through B.3 as 1.023.

Tables B.1 and B.2 show the calculations made to determine the displacement and trim of AVENGER for each day of the Standardization, Trial. The displacements and trims from these two tables were then averaged to get one displacement and trim for the Standardization Trial. The displacement during the Standardization Trial was 1,288 tons (1,309 t), and the trim was 1.33 ft (0.41 m) down by the stern.

Table B.3 shows the calculations made to determine the displacement and trim for the one day of Locked Shaft and Trailed Shaft Trials. The displacement and trim for these trials were 1,280 tons (1,301 t) and 1.66 ft (0.51 m) down by the stern, respectively.

It can be seen in Tables B.1 and B.2, that the displacement during the second day of the Standardization Trial was higher than that of the first day. An increase in displacement should not have been seen since fuel was used by the ship decreasing its displacement. When calculated, an error of +/- 1 in. in the draft readings resulted in an error of +/- 10 tons in the final displacement. The difference in displacement between the two days of the Standardization Trial is within this error range and most likely resulted from a slight error in the draft readings.

Table B.1. USS AVENGER (MCM 1) Standardization Trial, displacement calculation results, 19 June 1989.

LOCATION OF DRAFT MARKS		DRAFT READING	MEAN
FORWARD	PORT	10.67 ft	
			10.78 ft (3)
	STARBOARD	10.88 ft	
AMIDSHIP	PORT	11.00 ft (1)	
			11.36 ft (4)
	STARBOARD	11.71 ft (2)	
AFT	PORT	11.75 ft	
			12.13 ft (5)
	STARBOARD	12.50 ft	

Specific Gravity of Water (Corrected for Water Temp. = 81°F)	1.023
Specific Volume of Water = (35.955/Specific Gravity)	35.147 ft^3/ton (6)
Forward Draft Mark to Ref. Line for Longitudinal Centers	87.00 ft (7)
L.C.F. From Ref. Line at Draft (4) From Curves of Form (+ Aft, - Fwd)	15.55 ft (8)
Forward Draft Mark to L.C.F. = (7) + (8)	102.55 ft (9)
Forward Draft Mark to Midship Draft Mark	87.00 ft (10)
Forward Draft Mark to After Draft Mark	195.50 ft (11)
Trim Between Draft Marks = (5) - (3) (+ Aft, - Fwd)	1.35 ft (12)
Calculated Draft at Midship Draft Marks = (3) + [(12) * (10)]/(11)	11.38 ft (13)
Keel Deflection = (4) - (13) (+ Sag, - Hog)	-0.02 ft (14)
Calculated Draft at L.C.F. = (3) + [(12)* (9)]/(11)	11.49 ft (15)
Equivalent Draft = (15) + .75 * (14)	11.48 ft (16)
Displacement in Seawater at Draft (16) From Curves of Form	1,290 tons (17)
List = 57.3 * {[(2) - (1)]/121.00} (+ Port, - Stbd)	0.34 deg (18)
Final Displacement = (17) * [35/(6)]	1,285 tons (19)

Table B.2. USS AVENGER (MCM 1) Standardization Trial, displacement calculation results, 20 June 1989.

LOCATION OF DRAFT MARKS		DRAFT READING	MEAN
FORWARD	PORT	10.71 ft	
			10.80 ft (3)
	STARBOARD	10.88 ft	
AMIDSHIP	PORT	11.13 ft (1)	
			11.40 ft (4)
	STARBOARD	11.67 ft (2)	
AFT	PORT	11.83 ft	
			12.11 ft (5)
	STARBOARD	12.38 ft	

Specific Gravity of Water (Corrected for Water Temp. = 81°F)	1.023
Specific Volume of Water = (35.955/Specific Gravity)	35.147 ft^3/ton (6)
Forward Draft Mark to Ref. Line for Longitudinal Centers	87.00 ft (7)
L.C.F. From Ref. Line at Draft (4) From Curves of Form (+ Aft, - Fwd)	15.60 ft (8)
Forward Draft Mark to L.C.F. = (7) + (8)	102.60 ft (9)
Forward Draft Mark to Midship Draft Mark	87.00 ft (10)
Forward Draft Mark to After Draft Mark	195.50 ft (11)
Trim Between Draft Marks = (5) - (3) (+ Aft, - Fwd)	1.31 ft (12)
Calculated Draft at Midship Draft Marks = (3) + [(12) * (10)]/(11)	11.38 ft (13)
Keel Deflection = (4) - (13) (+ Sag, - Hog)	0.02 ft (14)
Calculated Draft at L.C.F. = (3) + [(12)* (9)]/(11)	11.49 ft (15)
Equivalent Draft = (15) + .75 * (14)	11.51 ft (16)
Displacement in Seawater at Draft (16) From Curves of Form	1,295 tons (17)
List = 57.3 * ([(2) - (1)]/121.00) (+ Port, - Stbd)	0.26 deg (18)
Final Displacement = (17) * [35/(6)]	1,290 tons (19)

Table B.3. USS AVENGER (MCM 1) Locked and Trailed Shaft Trials, displacement calculation results, 22 June 1989.

LOCATION OF DRAFT MARKS		DRAFT READING	MEAN
FORWARD	PORT	10.67 ft	
			10.59 ft (3)
	STARBOARD	10.50 ft	
AMIDSHIP	PORT	11.38 ft (1)	
			11.32 ft (4)
	STARBOARD	11.25 ft (2)	
AFT	PORT	12.25 ft	
			12.25 ft (5)
	STARBOARD	12.25 ft	

Specific Gravity of Water (Corrected for Water Temp. = 81°F)	1.023
Specific Volume of Water = (35.955/Specific Gravity)	35.147 ft^3/ton (6)
Forward Draft Mark to Ref. Line for Longitudinal Centers	87.00 ft (7)
L.C.F. From Ref. Line at Draft (4) From Curves of Form (+ Aft, - Fwd)	15.50 ft (8)
Forward Draft Mark to L.C.F. = (7) + (8)	102.50 ft (9)
Forward Draft Mark to Midship Draft Mark	87.00 ft (10)
Forward Draft Mark to After Draft Mark	195.50 ft (11)
Trim Between Draft Marks = (5) - (3) (+ Aft, - Fwd)	1.66 ft (12)
Calculated Draft at Midship Draft Marks = (3) + [(12) * (10)]/(11)	11.33 ft (13)
Keel Deflection = (4) - (13) (+ Sag, - Hog)	-0.01 ft (14)
Calculated Draft at L.C.F. = (3) + [(12)* (9)]/(11)	11.46 ft (15)
Equivalent Draft = (15) + .75 * (14)	11.45 ft (16)
Displacement in Seawater at Draft (16) From Curves of Form	1,285 tons (17)
List = 57.3 * ([(2) - (1)]/121.00) (+ Port, - Stbd)	-0.06 deg (18)
Final Displacement = (17) * [35/(6)]	1,280 tons (19)

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APPENDIX C

USS AVENGER (MCM 1) HULL ROUGHNESS SURVEY

A hull inspection and hull roughness survey was conducted on the USS AVENGER (MCM 1) on 11 June, 1989 at the Frederiksted Pier, St. Croix, U.S. Virgin Islands. This inspection was carried out by representatives of the David Taylor Research Center (DTRC). The hull roughness survey consisted of taking roughness measurements of AVENGER'S hull, shafting, rudders, and propellers. This survey is the baseline hull inspection and hull roughness survey for this ship.

A British Ship Research Association (BSRA) Mark II Roughness Analyzer was used to collect the peak-to-trough roughness measurements at representative locations throughout the hull area as well as on the ship's appendages and propellers. The BSRA Mark II measures the roughness in terms of the mean apparent amplitude.

The BSRA Hull Roughness Analyzer measures the maximum peak-to-trough height in micrometers for fifteen 50 mm (2.0 in.) sample lengths. These fifteen sample lengths are taken over a total of 750 mm (29.5 in.) of a length of surface. This length is known as one data length. For each data length, the individual values of the fifteen sample lengths are printed and the average of these fifteen values is printed. This average is the recorded roughness reading for that particular data length.

The BSRA trolley is moved across the surface in the direction of the water flow to yield the best results. The unit was operated in this manner throughout the hull survey unless otherwise noted.

There were thirty-six data length measurements made from the bow to the stern of the hull area. These thirty-six readings were averaged together to yield an overall hull roughness of 225 μm (0.00886 in.). The maximum hull roughness was 394 μm (0.01551 in.). The minimum hull roughness was 128 μm (0.00504 in.).

Readings were also taken on port and starboard rudders, shafting, and propellers. Average roughness readings on the port and starboard shafts were 193 μm (0.00760 in.) and 130 μm (0.00512 in.), respectively. The average roughness readings for the rudders were 196 μm (0.00772 in.) for the port rudder and 165 μm (0.00650 in.) for the starboard. The two propellers were found to be similar in roughness. The average roughness on the port propeller was 120 μm (0.00472 in.), while the average roughness on the starboard propeller was slightly lower at 102 μm (0.00402 in.).

Table C.1 is a summary of the hull roughness data recorded. It includes the name of the general area of the roughness readings, the number of roughness readings taken, and the roughness readings including maximum, minimum, and average values for each area.

Table C.2 shows a comparison of the roughness readings of AVENGER compared with USS THEODORE ROOSEVELT (CVN 71), USS MIDWAY (CV 41), USS WHIDBEY ISLAND (LSD 41), and USS VINCENNES (CG 49). It lists the average roughness values for the hull, rudders, and propellers. This table shows that the average readings for AVENGER are similar to readings done for the previous trials listed. From Tables C.1 and C.2 it can be seen that the AVENGER's hull was in suitable condition for the conduct of U.S. Navy first-of-class sea trials.

Table C.1. USS AVENGER (MCM 1) hull roughness data, 11 June 1989.

General Area	Number of Roughness Readings Taken	Maximum Roughness (µm)	(in.)	Minimum Roughness (µm)	(in.)	Average Roughness (µm)	(in.)
Hull	36	394	0.01551	128	0.00504	225	0.00886
Stbd Shaft	2	156	0.00614	103	0.00406	130	0.00512
Port Shaft	2	219	0.00862	166	0.00654	193	0.00760
Stbd Rudder	4	177	0.00697	154	0.00606	165	0.00650
Port Rudder	3	201	0.00791	193	0.00760	196	0.00772
Stbd Prop	4	128	0.00504	42	0.00165	89	0.00350
Port Prop	4	172	0.00677	40	0.00158	107	0.00421

Table C.2. USS AVENGER (MCM 1) hull roughness comparison.

Location	USS AVENGER (MCM 1) 6/11/89			USS THEODORE ROOSEVELT (CVN 71) 4/11/88 to 4/14/88			USS MIDWAY (CV 41) 4/6/87 to 4/7/87		
	No. of Roughness Readings	Average Roughness (µm)	Average Roughness (in.)	No. of Roughness Readings	Average Roughness (µm)	Average Roughness (in.)	No. of Roughness Readings	Average Roughness (µm)	Average Roughness (in.)
Hull	36	225	0.00886	62	264	0.01039	35	210	0.00827
Rudders	7	179	0.00705	15	291	0.01146	10	183	0.00720
Propellers	8	98	0.00386	31	112	0.00441	20	229	0.00902

Location	USS MIDWAY (CV 41) 8/22/86 to 8/24/86			USS WHIDBEY ISLAND (LSD 41) 3/24/87 to 3/27/87			USS VINCENNES (CG 49) 8/12/85 to 8/14/85		
	No. of Roughness Readings	Average Roughness (µm)	Average Roughness (in.)	No. of Roughness Readings	Average Roughness (µm)	Average Roughness (in.)	No. of Roughness Readings	Average Roughness (µm)	Average Roughness (in.)
Hull	85	233	0.00917	25	192	0.00756	68	140	0.00551
Rudders	14	194	0.00764	4	257	0.01012	4	250	0.00984
Propellers	30	118	0.00465	8	72	0.00283	-	-	-

APPENDIX D

USS AVENGER (MCM 1) PROPELLER PITCH CALIBRATION AND DETERMINATION

PITCH CALIBRATION

The pitch of both the starboard and port propellers on USS AVENGER (MCM 1) was surveyed by divers in Frederiksted, St. Croix, U.S. Virgin Islands on 10 and 11 June 1989. The survey was conducted 8 days prior to the Performance and Special Trials conducted 19 through 22 June 1989. This calibration was performed to determine the relationship between propeller pitch voltage output from the shaped feedback potentiometer as read by the DTRC trial computer, and the actual pitch as measured by divers.

The propeller pitch calibration used a device designed and fabricated by DTRC. This device, fastened to the propeller hub by divers, measured axial distances from a plane normal to the axis of the propeller shaft to the leading and trailing edges of each blade at 70% of the radius. The device was free to rotate 360° in this plane so that readings could be taken on all of the blades without removal of the device. The difference between the two measurements (Δ) is the axial distance between the leading and trailing edges. This axial distance, and the blade chord length (l) at 70% radius, were used in Eq. D.1. to calculate the propeller pitch angle.

$$\emptyset = \sin^{-1}(\Delta/l) \qquad \text{(D.1)}$$

where $\emptyset$ = pitch angle

Δ = axial distance from leading to trailing edges at 0.70 radius in inches

l = blade chord length at 0.70 radius in inches

For AVENGER, the blade chord length at 70% of the radius is 33.92 in. The pitch angle calculated in Eq. D.1 was then used in Eq. D.2 to calculate the propeller pitch at 70% radius.

$$P = 2\pi(0.70R)\tan\emptyset \qquad \text{(D.2)}$$

where   P = propeller pitch at 0.70 radius in feet

R = propeller radius in feet

The propeller radius for AVENGER is 3.50 ft. The ratio of this propeller pitch (calculated in Eq. D.2) to the design pitch yields the percent propeller pitch. For AVENGER the design pitch is 12.43 ft.

Each propeller was calibrated at five different pitch settings. For the first two pitch settings, maximum ahead and design, measurements were taken for all five of the blades on each propeller. Once it was established that all the blades were yielding the same pitch readings, readings were then reduced to two blades to save time. These measurements were then averaged to yield an average axial distance for the particular pitch setting. This axial distance was used in the above equations to calculate propeller pitch in terms of feet and percent of design at each setting.

The five pitch settings used for the calibration of the propellers on AVENGER were maximum ahead (120%), design (100%), 90%, centerline (31%), and maximum astern (-40%). Table D.1 lists the propeller pitch calibration data collected at two separate hydraulic oil operating temperatures. The table includes average propeller pitch in feet, average propeller pitch as percent of design, the shaped feedback potentiometer voltage, and hydraulic oil temperature in the pitch control system recorded manually from the gage located in the hydraulic oil pressure manifold.

Each propeller was pitch calibrated at two different pitch control system oil temperatures, so that the pitch readings taken during the trial could be corrected for varying oil temperature. The pitch calibration started after the systems had been allowed to warm up for three hours. Following the warm up period, the port system reached a temperature of approximately 128°F. At this temperature, voltage readings were taken at the five different pitch settings discussed earlier. After finishing this set of readings, the starboard system was calibrated four hours after the port system calibration was begun. During this calibration the starboard system was at a temperature of about 125°F. Following the starboard pitch calibration, the pitch control system hydraulic oil heaters were turned off and the systems were allowed to cool for 15 hours.

On 11 June 1989, the cold temperature calibration was begun. First, the starboard system was calibrated at a pitch control system oil temperature of approximately 113°F. This time, voltage readings were taken at only four pitch settings with the 90% pitch setting omitted. Following the starboard calibration, the port system was calibrated while at a temperature of about 120°F. This calibration was begun one and a half hours after the port system was started. Again, readings were taken at four pitch settings with the 90% setting left out. It should be noted that there was a delay on the second day of the calibration of about three hours, causing the temperatures for the cold calibration to be slightly higher than desired. DTRC personnel were hoping for cold calibration temperatures of between 100°F and 110°F, which would have shown a greater separation for the curves in Figs. D.1 and D.2.

The purpose of taking readings at two different temperatures was to develop pitch corrections as a function of pitch control system oil temperature which could be applied during the Standardization, Locked Shaft, and Trailed Shaft Trials. These corrections are needed because of the elongation of the pitch control rod with increasing temperature. This pitch correction is discussed in further detail in the next section. Figures D.1 and D.2 show the percent propeller pitch versus the voltage read by the computer for the port and starboard propellers at both oil temperatures.

The next two sections discuss the corrections to the pitch for variations in hydraulic oil temperature and for thrust compression. Since the propellers were calibrated in the same temperature water that the trials were run in, 81°F (27°C), pitch errors due to variations in ambient sea water temperature were not a factor.

PITCH CORRECTION DUE TO TEMPERATURE

The hydraulic oil temperature of the pitch control system is a critical factor in the determination of the actual propeller pitch. A small change in the temperature of the hydraulic oil causes a thermal expansion or contraction of the pitch control rod. This expansion or contraction of the pitch control rod changes the propeller pitch without changing the voltage read by the computer. During normal operation the temperature of the pitch control system oil will vary several degrees causing the propeller pitch to change. This change is not seen as a change in voltage by the DTRC trial computer; therefore when these voltages are converted to pitches, they do not reflect the actual pitch that the propellers were at during the trials. Each propeller was calibrated at two different oil temperatures so that propeller pitch could be corrected for variations due to thermal expansion.

This correction was accomplished by developing a set of correction curves for each propeller at each desired trial pitch. These curves are shown in Fig. D.3. As mentioned above, the data from the two pitch calibrations were plotted in Figs. D.1 and D.2. Linear curve fits were applied to each of the four sets of data shown in these figures. Since pitch corrections were desired for trial runs to be made at 90% and 100% pitch, voltage values corresponding to these pitches were interpolated from each of the four curves in Figs. D.1 and D.2. These interpolated values were then plotted on Fig. D.3. Linear curve fits were then applied to each of the four sets of data points in Fig. D.3. From these curves DTRC personnel could find the voltage required to achieve 90% or 100% pitch on either propeller at any pitch control system oil temperature. The equation for each line was calculated and a table, Table D.2, was made of potentiometer voltages required to achieve the desired pitch versus oil temperature, with temperature in 1°F increments.

Table D.2 was used to set the propeller pitch before each run during the trials. Setting the pitch was accomplished by determining the temperature of the oil in the system just before the run, reading the proper voltage needed to achieve the desired pitch, and matching the voltage read by the computer just before the run to this voltage. For example, suppose a run was to be made with a pitch setting of 100%, and that before the start of the run the temperature of the run was recorded at 125°F. From Table D.2, the voltages required to achieve 100% pitch on the port and starboard propellers are 4.06 V and 4.08 V, respectively at this temperature. DTRC personnel would then request that the propeller pitch controls be moved until this voltage was reached. This process of correcting the propeller pitch was used during the Standardization, Locked Shaft, and Trailed Shaft Trials on the AVENGER.

It should be noted that this method of achieving the correct pitch was not used for standardization runs performed at maximum ahead (120%) pitch. Since maximum ahead pitch is achieved when the pitch control rod is pushed against its stops, DTRC personnel used the hub servo oil pressure gage to determine the point at which this occurred. This determination is possible since there is a hydraulic oil pressure spike, indicated on the hub servo oil pressure gage, when the pitch control rod reaches its stops. For runs made at maximum ahead pitch, the pitch was set by observing this pressure spike then backing off on the pressure slightly so as not to put unnecessary strain on the pitch control rods.

After the conduct of the trials on AVENGER there were still some corrections to be made to the pitches on the propellers. The starboard shaft, which was not driving the ship during the Locked Shaft and Trailed Shaft Trials, was not corrected during the trials because it was not felt that this pitch was as critical as the pitch on the driving shaft, and some variation due to temperature change would be tolerable. The correct pitches on the starboard shafts were determined, upon returning from the trials, by interpolating between the curves in Fig. D.2 using the temperature of the starboard pitch control system during each run and the recorded potentiometer voltage. This method was used on all of the pitch data to back out the pitches on both shafts from the voltages recorded by the trial computer.

In summary, the pitch on controllable reversible pitch propellers changes as the temperature of the pitch control system hydraulic oil changes. This pitch change is not seen as a voltage change in the potentiometer. In the past, DTRC has corrected this data upon returning from the trial, resulting in pitches which were slightly off from those desired. For trials on the AVENGER, DTRC personnel chose to perform this temperature correction during the trials using the voltages and oil temperatures recorded prior to each run to achieve the desired pitches. It can be seen in Tables 4 through 7 that this method worked well in achieving the desired pitches.

PITCH CORRECTION DUE TO THRUST

In addition to the propeller pitch correction due to variations in pitch control system hydraulic oil operating temperature, a correction was also made to the propeller pitch for thrust compression. As thrust is developed by the propellers, the force tends to compress the propeller shaft but not the pitch control rod. This compression makes the pitch control rod seem longer relative to the propeller shaft, and results in a slight pitch change which is not reported in the feedback potentiometer voltages. The decrease in propeller shaft length due to thrust compression can be calculated using Eq. D.3.

$$\Delta L = (T/E)(L/A) \qquad \text{(D.3)}$$

where ΔL = change in shaft length due to compression (in.)

T = thrust (lb)

E = modulus of elasticity (for AVENGER $E = 26.0 * 10^6$ lb/in^2)

L = shaft length (in.)

A = cross-sectional area of shaft (in^2)

Since the cross-sectional area for the shafts on AVENGER varied at different points, the shaft was broken into various lengths and corresponding cross-sectional areas. The change in length of each section of the shaft was calculated and the results added to get the total change in shaft length.

It is possible to measure shaft thrust using load cells located in the thrust bearing, but since this was not done for trials on the AVENGER the thrust at various ship speeds was estimated using model data. For this estimation Eqs. D.4 and D.5 were used.

$$R_T = [(P_E)(33{,}000)]/[(V)(101.33)] \qquad \text{(D.4)}$$

where R_T = hull resistance (lb)

P_E = effective power (hp)

V = ship speed (kn)

$$T = R_T/(1-THDF) \quad (D.5)$$

where T = total thrust (lb)

$THDF$ = thrust deduction factor

In Eqs. D.4 and D.5 above, P_E, V, and THDF were taken from Table 5 in DTRC report DTNSRDC/SPD-0983-10.[2] At these various ship speeds corresponding thrusts were computed. Since the computed thrusts from the above equations were total thrusts, they had to be divided by two for use in Eq. D.3. Once the total change in length due to shaft compression (ΔL) was computed, then the percent pitch change due to thrust compression could be calculated using Eq. D.6.

$$\Delta P = [(\Delta L)/(L_{CR})](P_R) \quad (D.6)$$

where ΔP = pitch change due to thrust compression (%)

L_{CR} = range of control rod travel during trials (for trials on AVENGER L_{CR} = 0.875 in.)

P_R = range of propeller pitch during trials (for trials on AVENGER P_R = 30%)

The changes in pitch due to thrust compression calculated at various speeds were plotted on Fig. D.4. This curve represents the correction which must be applied to the pitch data as a function of ship speed. Since thrust compression only reduces propeller pitch, these correction factors were subtracted from the pitch values already corrected for oil temperature. The pitch data shown in Tables 4 through 7 are thus corrected for both oil temperature variations and shaft thrust compression. It can be seen in Tables 4 through 7, that the propeller pitches are shown to the nearest 1% and the corrections here are all less than 1% of design pitch. Measurements obtained by the divers during the pitch calibration were repeatable to the nearest 1/8 in. or 1%; therefore the final pitches were rounded to this number. The pitch corrections described in this section, were subtracted prior to the rounding of the propeller pitches and are therefore included in the final results.

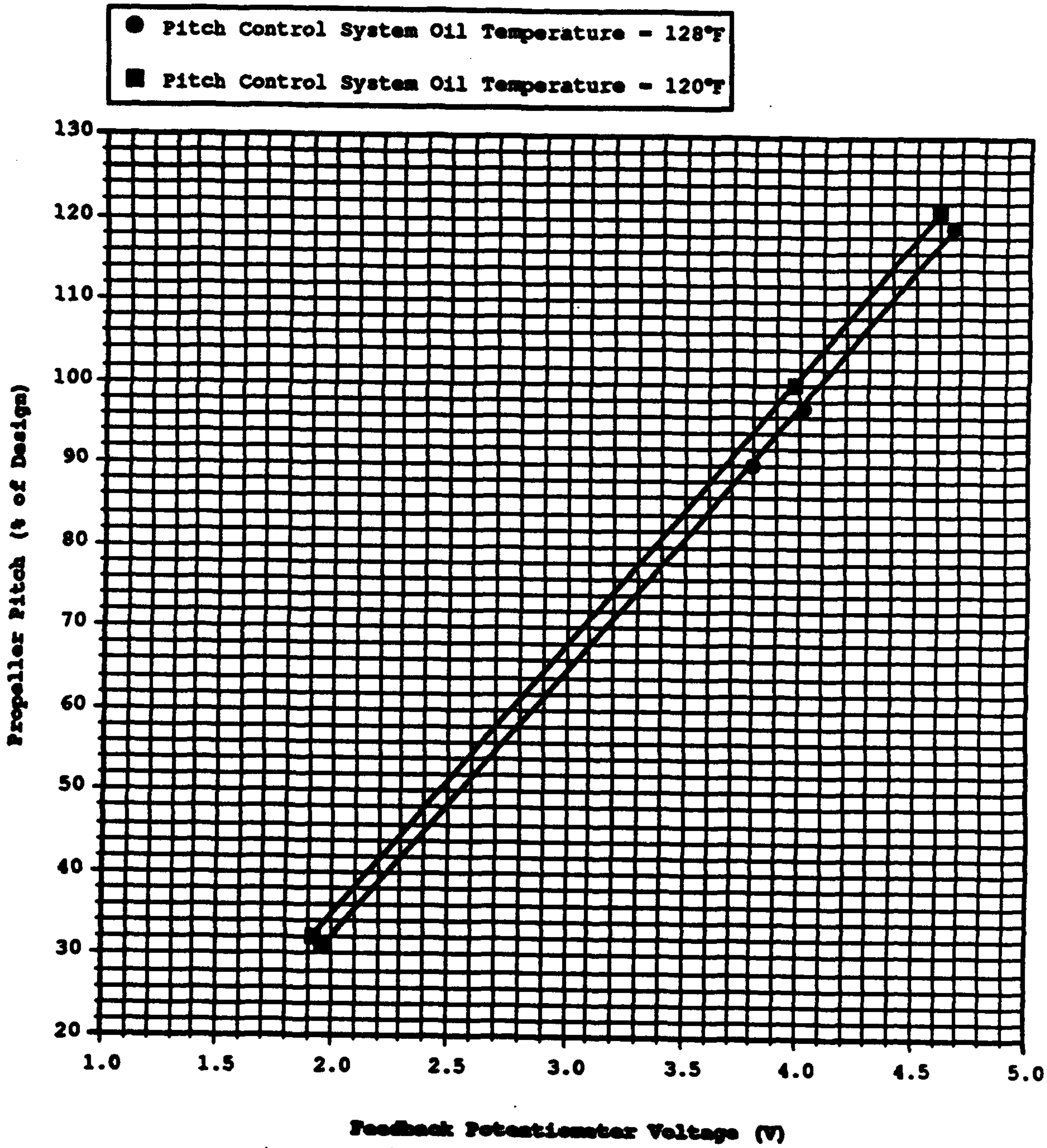

Fig. D.1. USS AVENGER (MCM 1) port propeller pitch calibration results.

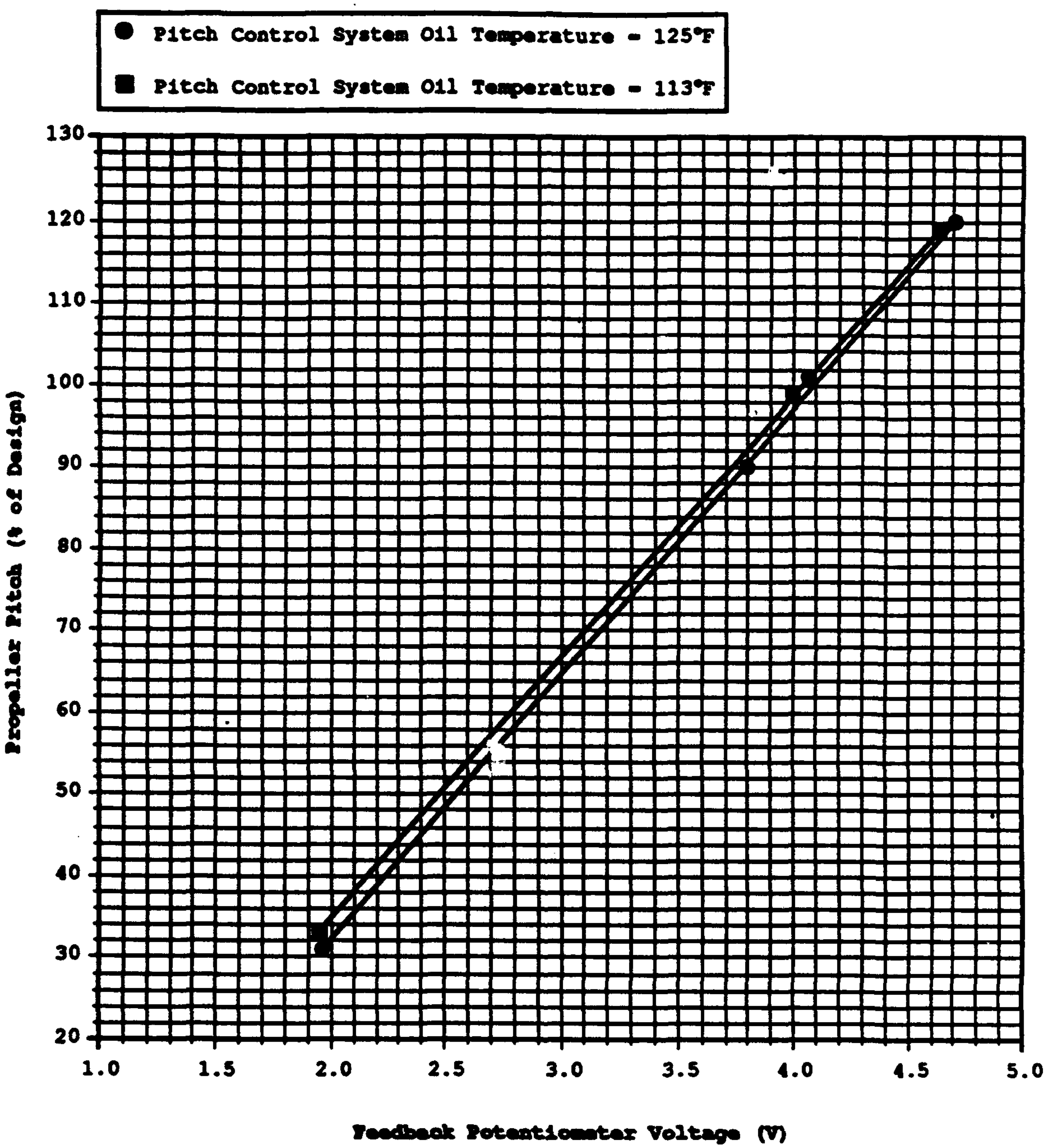

Fig. D.2. USS AVENGER (MCM 1) starboard propeller pitch calibration results.

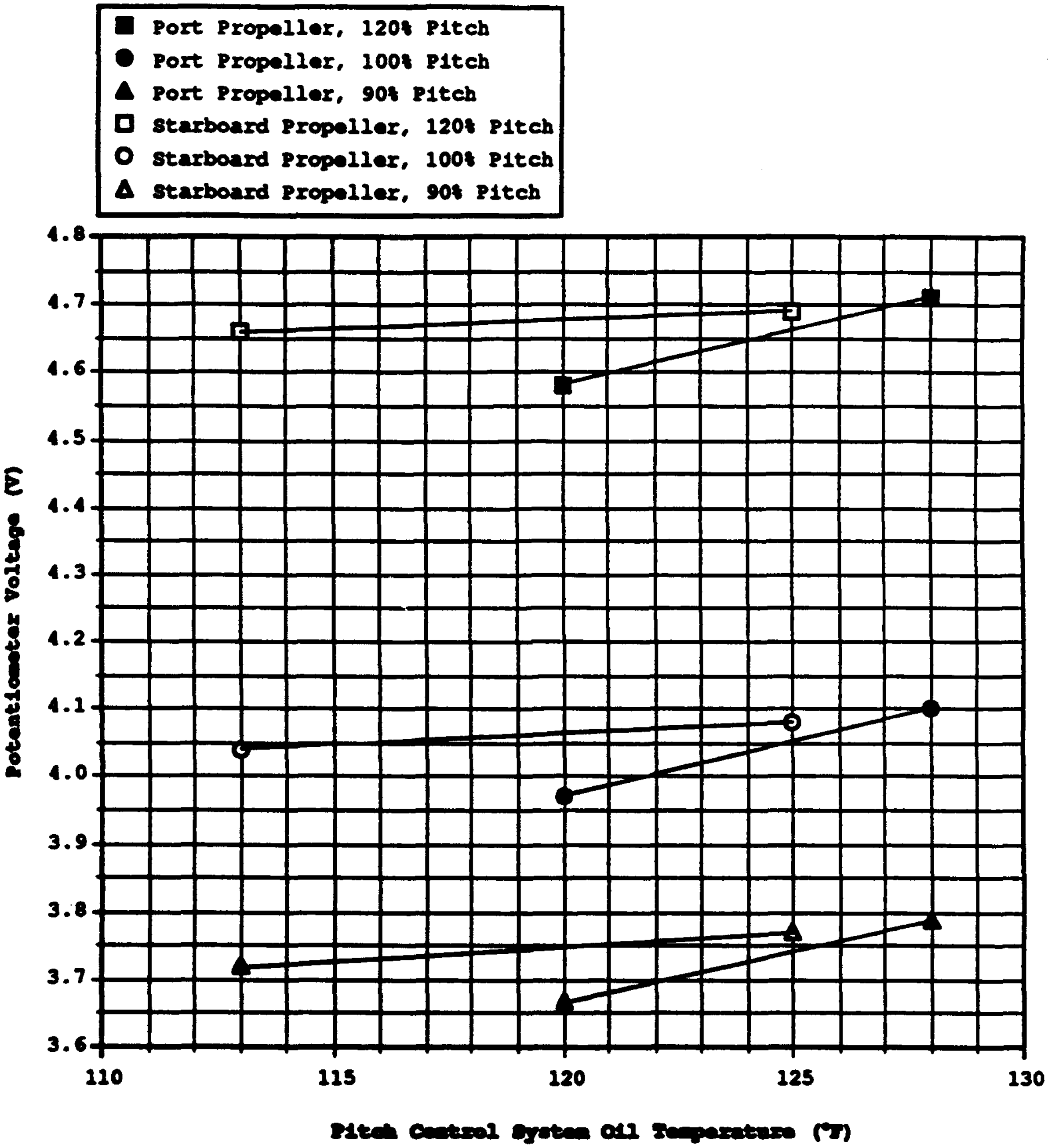

Fig. D.3. USS AVENGER (MCM 1) port and starboard potentiometer voltage versus pitch control system hydraulic oil temperature.

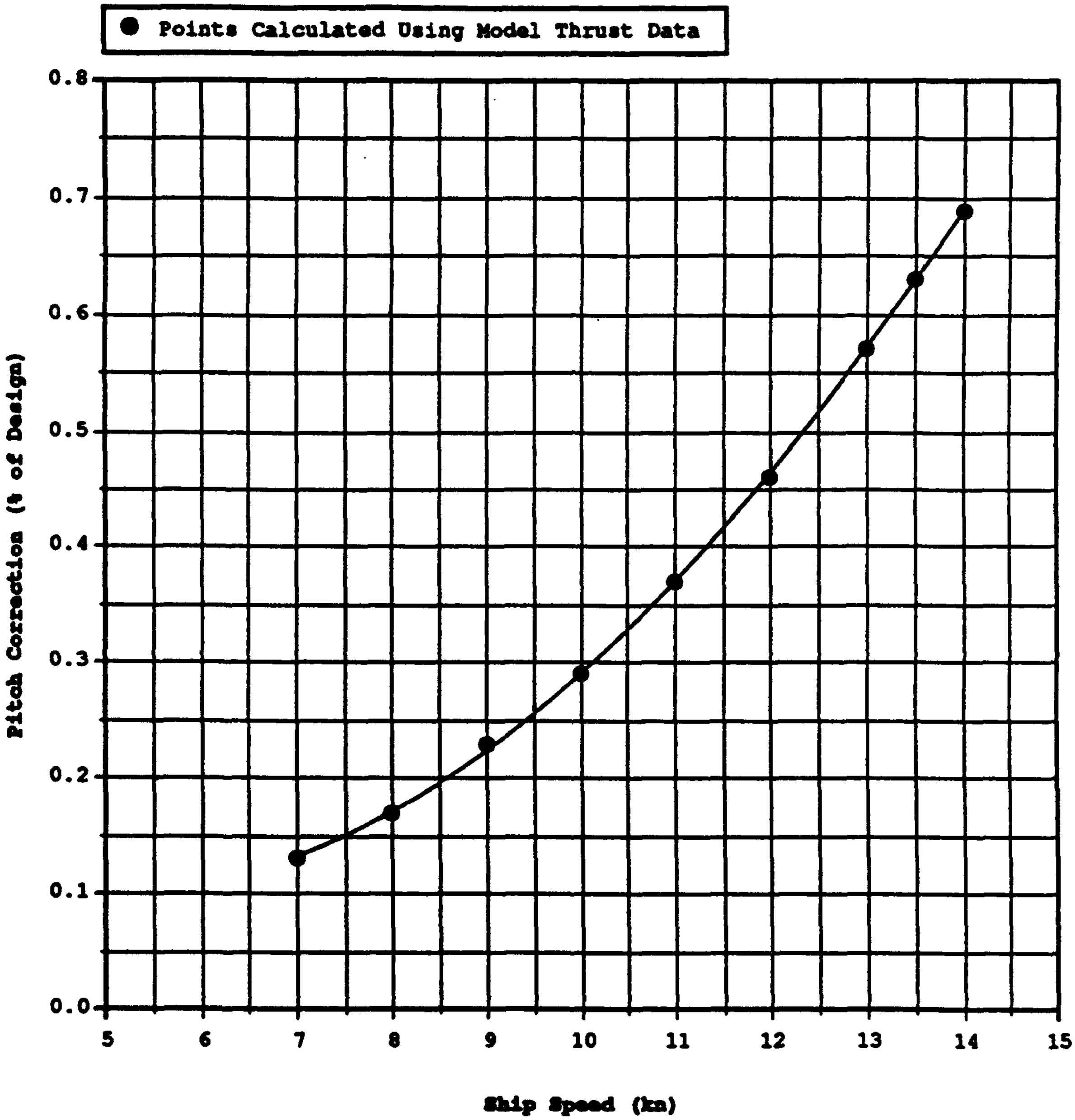

Fig. D.4. USS AVENGER (MCM 1) correction for change in propeller pitch due to thrust compression.

Table D.1. USS AVENGER (MCM 1) propeller pitch calibration results.

Propeller Pitch Reading from O.D. Box Pointer	Average Propeller Pitch (ft)	Average Propeller Pitch (% of Design)	Shaped Potentiometer Voltage (V)	Pitch Control System Oil Temperature (°F)
Port Propeller, Hot Pitch Calibration, 6/10/89				
FAD	14.8	119	4.67	128
12.0'	12.1	97	4.02	128
11.0'	11.1	90	3.79	128
2.5'	3.9	31	1.96	128
FAS	-5.1	-41	0.00	127
Port Propeller, Cold Pitch Calibration, 6/11/89				
FAD	15.1	121	4.60	119
12.0'	12.4	100	3.98	120
2.5'	4.0	32	1.92	120
FAS	-4.8	-39	0.00	120
Starboard Propeller, Hot Pitch Calibration, 6/10/89				
1/16" above FAD	14.9	120	4.71	126
12.4'	12.5	101	4.07	126
11.1'	11.2	90	3.80	125
2.7'	3.9	31	1.96	125
1/8" below FAS	-5.5	-44	-0.01	124
Starboard Propeller, Cold Pitch Calibration, 6/11/89				
FAD	14.8	119	4.63	112
12.0'	12.4	100	4.00	113
2.7'	4.1	33	1.95	113
1/4" below FAS	-5.3	-42	-0.01	113

Table D.2. USS AVENGER (MCM 1) port and starboard potentiometer voltages required to achieve desired pitches at various pitch control system hydraulic oil temperatures.

Pitch Control System Oil Temp. (°F)	Potentiometer Voltage to Achieve 90% Pitch		Potentiometer Voltage to Achieve 100% Pitch	
	Starboard	Port	Starboard	Port
100	3.67	3.37	3.99	3.65
101	3.67	3.39	4.00	3.67
102	3.68	3.40	4.00	3.68
103	3.68	3.42	4.00	3.70
104	3.69	3.43	4.01	3.72
105	3.69	3.45	4.01	3.73
106	3.69	3.46	4.01	3.75
107	3.70	3.48	4.02	3.76
108	3.70	3.49	4.02	3.78
109	3.71	3.51	4.02	3.80
110	3.71	3.52	4.03	3.81
111	3.72	3.54	4.03	3.83
112	3.72	3.55	4.03	3.85
113	3.72	3.57	4.04	3.86
114	3.73	3.58	4.04	3.88
115	3.73	3.60	4.04	3.89
116	3.74	3.61	4.05	3.91
117	3.74	3.63	4.05	3.93
118	3.74	3.64	4.05	3.94
119	3.75	3.66	4.06	3.96
120	3.75	3.67	4.06	3.98
121	3.76	3.69	4.06	3.99
122	3.76	3.70	4.07	4.01
123	3.77	3.72	4.07	4.02
124	3.77	3.73	4.07	4.04
125	3.77	3.75	4.08	4.06
126	3.78	3.76	4.08	4.07
127	3.78	3.78	4.08	4.09
128	3.79	3.79	4.09	4.11
129	3.79	3.81	4.09	4.12
130	3.80	3.82	4.09	4.14
131	3.80	3.84	4.10	4.16
132	3.80	3.85	4.10	4.17
133	3.81	3.87	4.10	4.19
134	3.81	3.88	4.11	4.20
135	3.82	3.90	4.11	4.22
136	3.82	3.91	4.11	4.24
137	3.82	3.93	4.12	4.25
138	3.83	3.94	4.12	4.27
139	3.83	3.96	4.12	4.29
140	3.84	3.97	4.13	4.30

APPENDIX E

USS AVENGER (MCM 1) TORSIONMETER COMPARISON

During the Performance and Special Trials on USS AVENGER (MCM 1) personnel from DTRC had the opportunity to install both of the two types of torsionmeter systems used in the past on MCM trials. The shafting characteristics and torsionmeter data for these two systems are shown in Table E.1. Data were collected from both DTRC torsionmeter systems during the trials and a comparison of the data is shown in Figs. E.1 through E.3. It can be seen throughout these figures that at the same shaft speed and same propeller pitch, the port shaft 1645 torsionmeter was reading significantly higher than the port shaft 1200 system, the starboard shaft 1200 system, and the starboard shaft 1645 system.

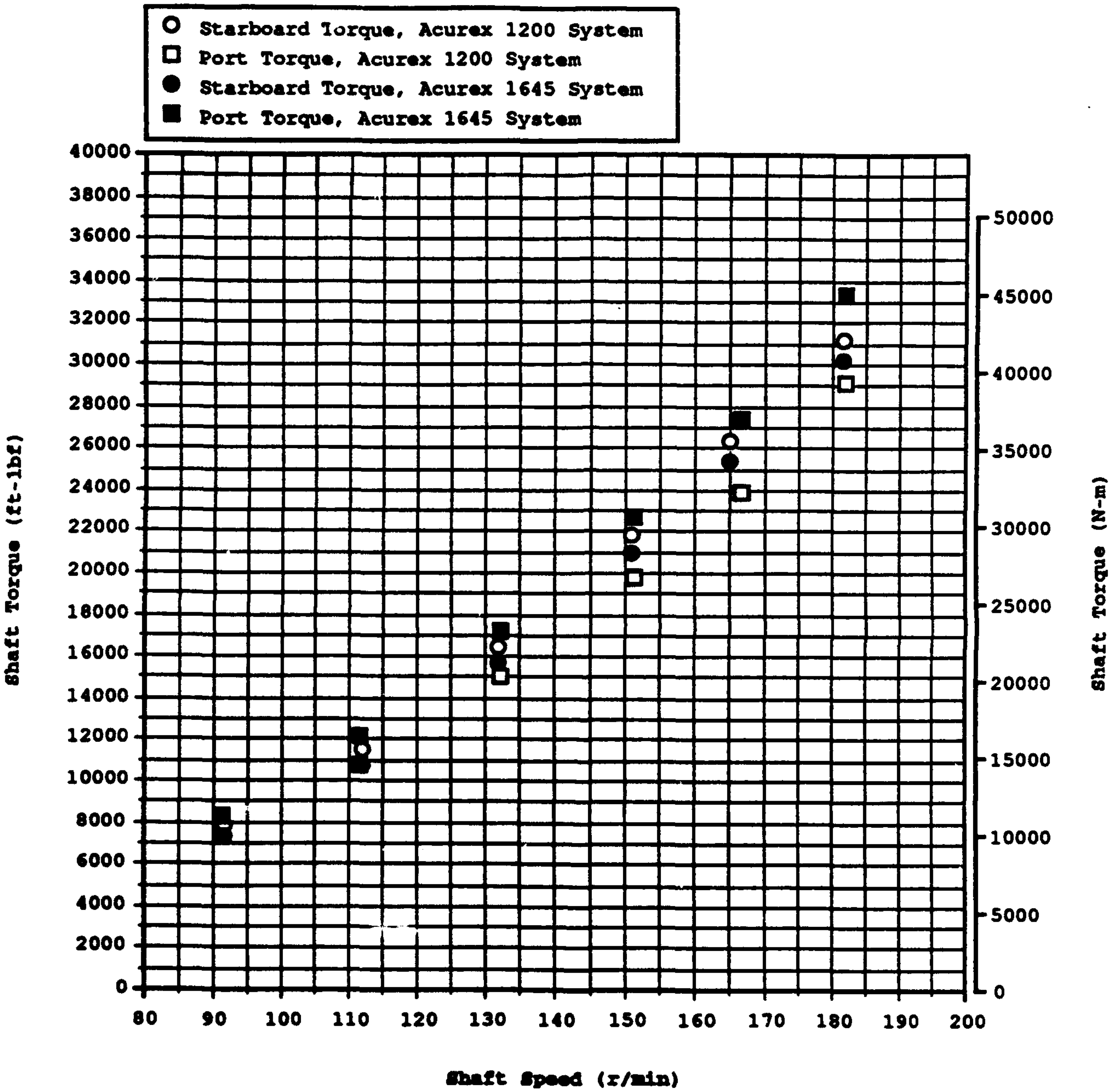

Fig. E.1. USS AVENGER (MCM 1) torsionmeter comparison, nominal 100% pitch.

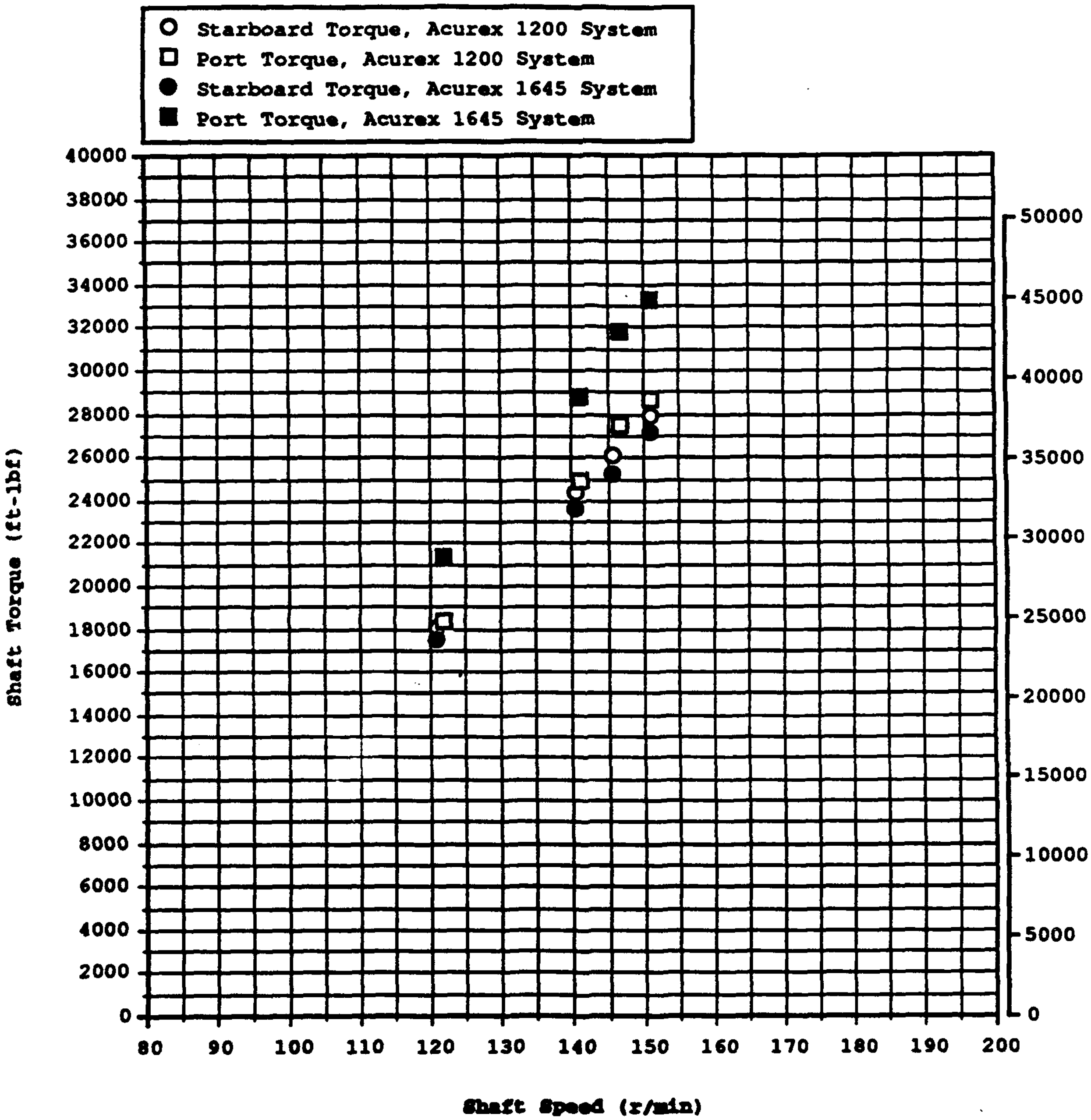

Fig. E.2. USS AVENGER (MCM 1) torsionmeter comparison, nominal 120% pitch.

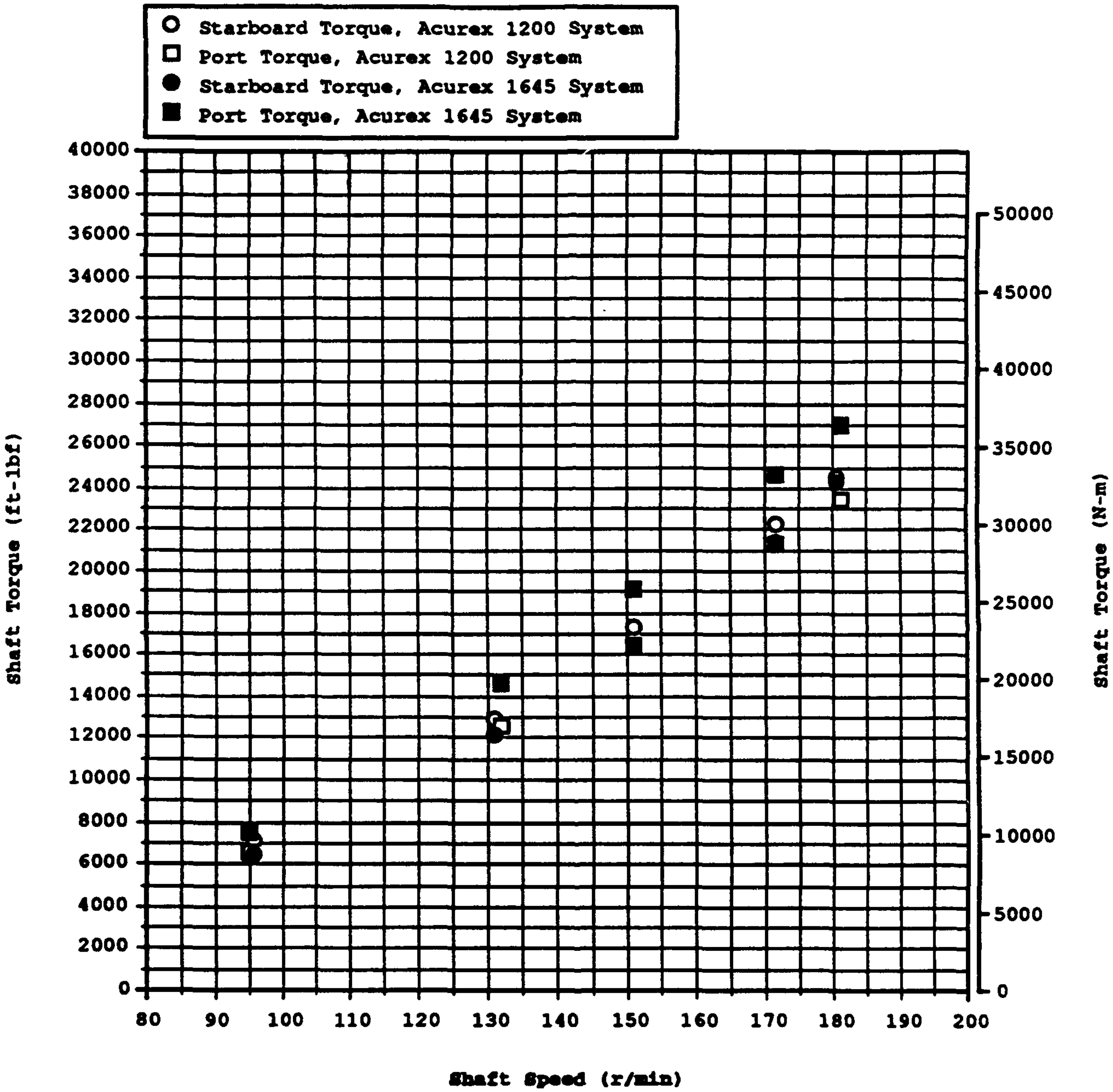

Fig. E.3. USS AVENGER (MCM 1) torsionmeter comparison, nominal 90% pitch.

Table E.1. USS AVENGER (MCM 1) torsionmeter data.

	Starboard Shaft	Port Shaft
Acurex 1645 Torsionmeter System		
Shaft Material	Copper Alloy Number 953 (Heat-Treatable Cast Aluminum Bronze)	
Shaft outside diameter, in. (cm)	13.506 (34.305)	13.511 (34.318)
Shaft inside diameter, in. (cm)	12.400 (31.496)	12.400 (31.496)
Modulus of rigidity $lb/in.^2$ (kPa)	6,580,000 (45,400,000)	6,580,000 (45,400,000)
Ring serial number	196	197
Distance between knife edges, in. (cm)	17.136 (43.525)	17.142 (43.541)
Ring bore, in. (cm)	13.498 (34.285)	13.500 (34.920)
Sensor serial number	2-338	2-435
Electronics serial number	1-326	272-83
Trial gain, ft-lbf/mV (N-m/mV)	4.559 (6.181)	7.301 (9.899)
Trial zero, mV	-103	-40
Acurex 1200 Torsionmeter System		
Shaft Material	K-monel	K-monel
Shaft outside diameter, in. (cm)	7.480 (18.999)	7.480 (18.999)
Shaft inside diameter, in. (cm)	2.500 (6.350)	2.500 (6.350)
Modulus of rigidity $lb/in.^2$ (kPa)	10,065,000 (69,400,000)	10,065,000 (69,400,000)
Trial gain, ft-lbf/mV (N-m/mV)	5.000 (6.779)	5.000 (6.779)
Trial zero, mV	-27	-18

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