The Design and Service Experience of the *Polar Endeavour* Class Tankers

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ABSTRACT

The Polar Endeavour *(Millennium) Class Tankers, represent the first U. S. flag crude oil carriers designed and built for the Alaskan Trade in compliance with the Oil Pollution Act of 1990 (OPA90). These vessels represent the start of a revolution in design for American crude carriers. Not only are they fitted with double hulls, which are deeper than required, but also they are fitted with twin independent engine rooms, and twin rudders. They are the first vessels to be classed R2-S+ and NIBS under the American Bureau of Shipping's (ABS) Guidelines for Redundant Propulsion Systems and Navigation Integrated Bridge Systems. The vessels meet the requirements for Annex VI of MARPOL for air emissions, and are painted with tin free (TBT) anti-foul paints. This paper describes the design development process used and the unique and innovated design, which resulted. Three vessels have entered service in 2001, 2002 and 2003 and two are under construction for delivery in 2004 and 2005.*

[1] The opinions expressed in this paper are those of the author and do not reflect those of Polar Tankers Inc., ConocoPhillips Marine, ConocoPhillips Alaska or the ConocoPhillips Corporation.

ACRONYMS

+A1E	Compliance with ABS Rules for Self-Propelled Vessels & Equipment Standards
AB	Able Bodied Seaman
ACCU	Compliance with ABS Automatic Centralized Control Unmanned Criteria
ADSSE	Automatic Dependent Surveillance Shipborne Equipment
AIS	Automatic Identification System
AMS	Compliance with ABS Machinery Requirements
ANS	Alaska North Slope
ANTS	Automated Navigation & Tracking System
APS	Compliance with ABS Athwartship Thruster Criteria
ARPA	Automatic Radar Plotting Aid
bbls	Barrel (42 gallons U.S.)
BHP	Brake Horsepower
BHPh	Brake Horsepower-Hour
CAIP	USCG Critical Area Inspection Program
C_b	Block Coefficient
CFD	Computational Fluid Dynamics
COI	USCG Certificate of Inspection
COW	Crude Oil Washing
CP	Controllable Pitch
cSt	Viscosity – Centistokes
DGPS	Differential Global Positioning System
DL	Compliance with ABS Dynamic Load Approach
DLA	Dynamic Load Approach
DNV	Det Norske Veritas
DWT	Deadweight
ECDIS	Electronic Chart Display & Information System
EPA	Environmental Protection Agency
FEA	Finite Element Analysis
g/BHPh	Grams per Brake Horsepower-Hour
g/kWh	Grams per Kilowatt-Hour
GLONASS	Russian Equivalent to GPS
GMDSS	Global Marine Distress & Safety System
GPS	Global Positioning System
H1/3	Significant Wave Height
HFO	Heavy Fuel Oil
HV	High Voltage
HZ	hertz (Frequency in cycles/second)
IG	Inert Gas
IGS	Inert Gas System
IMO	International Maritime Organization
I/O	Input/Output
ISO	International Standards Organization
Kcal/kg	Kilocalorie/kilogram
kJ/kg	Kilojoules/kilogram
KV	Kilovolts
KW	Kilowatts
LAN	Local Area Network (Computer)
LBP	Length Between Perpendiculars
LCB	Longitudinal Center of Buoyancy
LV	Low Voltage
L_{OA}	Length, Overall
L_{PP}	Length, Between Perpendiculars
LSFO	Low Sulfur Fuel Oil
LT	Long Tons
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Machinery Control Room
MCR	Maximum Continuous Rating
MCS	Machinery Control Space
MCS	Machinery Control System
MDO	Marine Diesel Oil
MDL	Marine Dynamics Laboratory (SSPA Maritime Consulting)
MDWT	1,000 Deadweight Tons
mil	1/1000 of an inch
MT	Metric Tons
MW	Megawatt
NIBS	Compliance with ABS Navigational Integrated Bridge System Criteria
OPA90	Oil Pollution Act of 1990
OS	Operating Station
PC	Personal Computer
PCU	Power Converter Unit
PMS	Power Management System
PTI	Polar Tankers Inc.
PTO	Power Take Off
psig	Pressure - Pounds per Square Inch Gage
QMED	Qualified Member of the Engine Department
R2-S+	Compliance with ABS Criteria for Redundant Propulsion & Steering Systems with Adverse Weather Endorsement
ROB	Retained on Board
RPS	Redundant Propulsion & Separate
SH	Compliance with ABS SafeHull Criteria
SHP	Shaft Horsepower
SOLAS	International Convention for Safety of Life at Sea
T	Draft
T_f	Draft, Forward
T_a	Draft, Aft
TAPS	Trans-Alaska Pipeline System
TBT	Tri-butyl Tin
UHF	Ultra High Frequency Radio
UWILD	Compliance with ABS Underwater Hull Survey Criteria
VHF	Very High Frequency Radio
VTS	Vessel Traffic System

DESIGN

OPA90 not only created a requirement for new tankers to be fitted with double hulls, it also brought with it cargo owner liability. Cargo owner liability places financial responsibility not only on the Owner/Operator of the vessel, but on the cargo owner as well. For a company like Polar Tankers Inc. (Polar)[2], an Owner/Operator, and through its association with its parent company, a cargo owner, all responsibilities lie at one doorstep. It is recognized that the 80/20 rule applies to tanker accidents, that 80% are caused by human error, and 20% by mechanical failure. Polar had invested large sums of time and money in crew and officer training in order to reduce the human error portion of the 80%. However, there was still an inherent portion of the 80% that resulted from how U.S. tankers were acquired, and a majority portion of the 20% had gone without being addressed.

Polar, in reviewing its existing vessels, and in looking at world class vessels found, in retrospect, not so amazing conclusions. Historically, Polar's tankers were standard shipyard designs, equipped with machinery supplied by the low bidder. Design changes were expensive and served only to correct unacceptable flaws. Chosen equipment, while serviceable, represented a long-term maintenance and repair commitment. Ergonomics, habitability, redundancy, maintainability, and reliability were concepts that were either not known or ignored. Therefore, to reduce the possibility of accidents Polar had to develop a vessel designed to be operated easily and efficiently by the operators with a reduced likelihood of error. The vessels had to first be reliable using proven state of the art equipment. The vessels had to be easily maintained by the crew. And most importantly, to insure the vessel's safety was not compromised in the event of a failure, they had to be fully redundant.

The origin in design of the *Endeavour* Class vessels can be traced to the North Sea shuttle tankers, and in particular, the vessels owned and operated by Knutsen AB, and designed and built by IZAR (formerly Astilleros Espanoles, S.A.). Designed for loading at offshore facilities in heavy weather (Sea State 7 and greater), the twin screw, twin rudder tankers, with high lift rudders and multiple bow and stern thrusters, are capable of dynamic positioning, and operate daily in a highly efficient system. These vessels provided the design basis by which Polar established the design of the *Endeavour* Class vessels.

Knutsen and IZAR also provided insights into equipment and manufacturers. While equipment exhibitions such as SMM™ in Hamburg and Norshipping™ in Oslo provided exposure to a wide variety of equipment, Knutsen and IZAR provided information regarding good, better, and best. They provided information on favorites and preferences, on equipment they were using, and equipment they wished they were using. They opened the door to the world of marine equipment, a world not often visited by American owners and American shipyards.

In addition to the help from Knutsen and IZAR, Polar also sought insight and opinion from within. Polar's predecessors, Atlantic Refining and Arco Marine, Inc., had been operating tankers since 1916. In particular, they had been operating tankers in the Alaskan Trade since the early 1970's and specifically in the Trans-Alaska Pipeline (TAPS) Trade since the pipeline opened in 1978. Polar had at its fingertips data on structural fatigue and problems associated with the severe weather and high cyclical loadings and short runs in heavy weather. Typical tankers may make 8 or 10 voyages in a year, and 250 in a lifetime. Polar's make up to 33 a year and 550-600 in a lifetime.

Long term exposure to the elements provided a wealth of information on machinery reliability and maintainability. We knew what worked, but perhaps more importantly, what didn't. With the voyages and the weather come the sea stories and the anecdotal information. From this information comes the data needed to direct design on ergonomics and habitability. It is our belief that anyone sailing, past or present, in Polar's fleet can proclaim, "I'm responsible for that! I told them it needed to be done." From lighting on deck and in the engine rooms, to athwartship arrangement of bunks, from single messes and lounges to a conference room, from raised catwalks to a cargo control room on "A" deck, Polar employees can claim responsibility.

The *Endeavour* Class tankers represent a transition in design from what the shipyards believed the owner needed in the 1970s, to a ship an owner/operator wants for today and for the future.

Table 1 provides a list of particulars for the *Endeavour* Class tankers. Figures 1 and 2 show the general arrangement for the vessels.

Table 1 - Vessel Particulars

Principal Characteristics	
Length, Overall (L_{OA})	272.96m
Length, Between Perpendiculars (L_{PP})	258.16m

[2]Polar Tankers Inc. and ConocoPhillips Alaska, Inc. are wholly owned subsidiaries of ConocoPhillips. Polar Tankers manages the marine transportation of ConocoPhillips Alaska's North Slope production of Alaska North Slope (ANS) crude oil. Polar Tankers has become part of ConocoPhillips Marine but continues to maintain its Long Beach, California headquarters. ConocoPhillips Marine includes several marine related companies along with Polar Tankers, Conoco Shipping, and Emerald Shipping.

Beam, Molded	46.20m
Depth, Molded (At Side)	25.30m
Depth, Molded (At Centerline)	26.30m
Draft, Design	16.19m
Draft, Scantling	17.52m
Lightship Weight	31,769 MT
Gross Tonnage	85,387 MT
Net Tonnage	41,995 MT
Capacity, Design	125,000 LT
Deadweight, Design Draft	127,005 MT
Displacement, Design Draft	158,774 MT
Capacity, Scantling	139,436 LT
Deadweight, Scantling Draft	141,734 MT
Displacement, Scantling Draft	173,506 MT

Capacities (100%)	
Cargo Tanks (1,014,100 bbls)	161,526m^3
Ballast Tanks	62,362m^3
HFO Tanks	4,415m^3
LSFO Tanks	615m^3
DO Tanks	552m^3
Fresh Water Tanks	189m^3

MODEL TESTING

Background

Historically, Polar's experiences were that model testing was the sole responsibility of the shipyard. As a result, the model test program was limited to resistance and propulsion testing. This testing provided assurance to the shipyard that speed/power requirements would be met. Wind tunnel testing was done on occasion because of smoke problems, and cavitation testing was done only after severe propeller damage was encountered. Review of past Polar vessels showed that shipyards stopped testing when a design point was reached and rarely, if ever, was the optimum design point ever sought. Seakeeping and maneuverability were two concepts that were not studied, and in general were never considered.

In some cases Polar had vessels that performed as designed. In other cases we had vessels that performed to expectations only on those days they encountered calm weather conditions found in model basins. On one class of ships, when we later started studies to improve performance, we received documentation from the model basin showing they had advised the shipyard during the design process that the basin's "Preliminary" lines had been used by the yard as "Final" lines. We believe this information was provided out of fear that the basin's reputation might be soiled because the yard didn't wish to invest in another round of testing. This documentation indicated that the vessel was likely to encounter severe performance degradation in heavy weather, and was likely to experience cavitation and vibration problems. The shipyard, to meet schedule, used their "Final" lines. These vessels, as predicted by the basin, perform poorly in seaways, vibrate, and suffer cavitation problems.

For the *Endeavour* Class vessels, Polar set out to control the hull design. Instead of having the shipyard contract with a model basin, Polar sought out model basins and chose the basin they felt was best suited to work with them in producing an optimum design. Basin selection criteria were facilities, experience designing shuttle type tankers, the ability for the basin, Polar and Polar's design team to work cooperatively, and last of all, cost. Polar's design program included not only development of lines, and resistance and propulsion testing. The program also included computational fluid dynamics (CFD) evaluation of a preliminary set of lines and a set of lines developed by the model basin, computer simulation of maneuvering characteristics for rudder selection, resistance and propulsion testing on the 'initial" lines from the CFD study with a paint flow test and wake survey, development of "final" lines, resistance and propulsion testing with a wake survey using library propeller, propeller design, cavitation tunnel testing with a design propeller, resistance and propulsion testing with a design propeller, seakeeping testing, maneuverability testing, wind tunnel testing, and disabled ship maneuverability. Kamewa, as part of their contract as the provider of the propellers, was required to do resistance and propulsion testing as well as cavitation testing for their final propeller design.

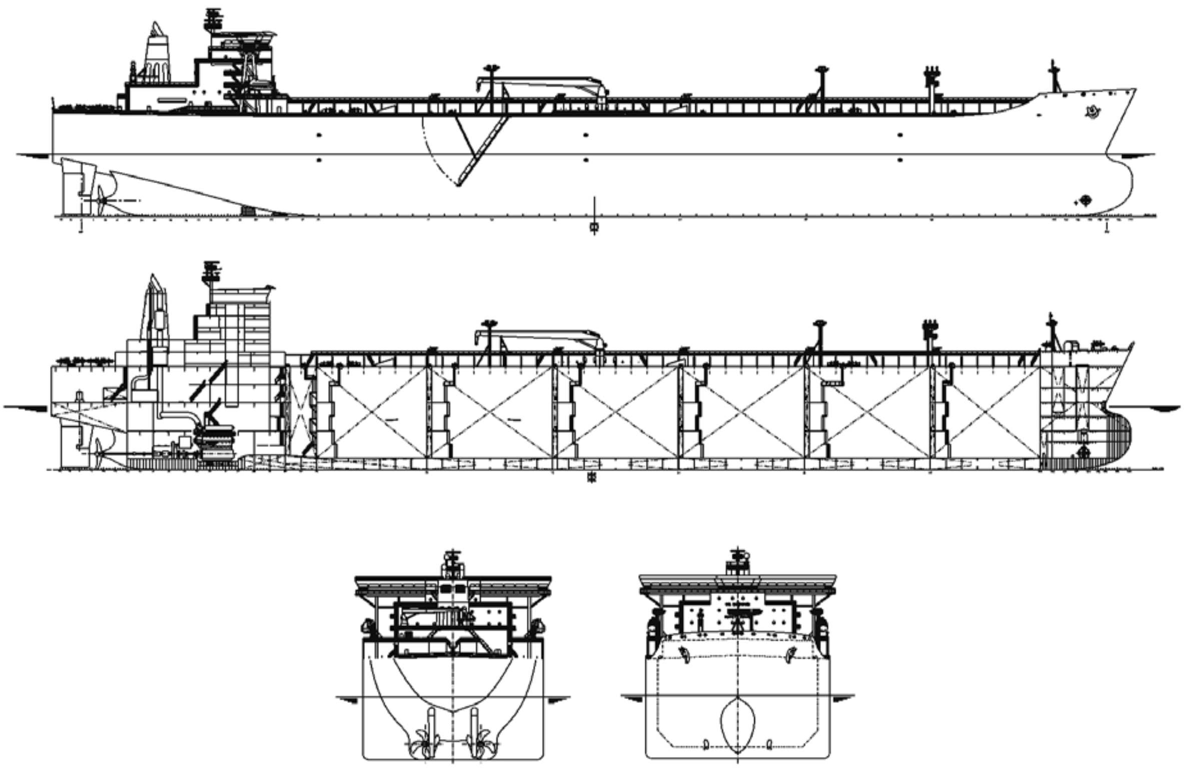


Fig. 1 Inboard Profile, Outboard Profile, Bow and Stern Views

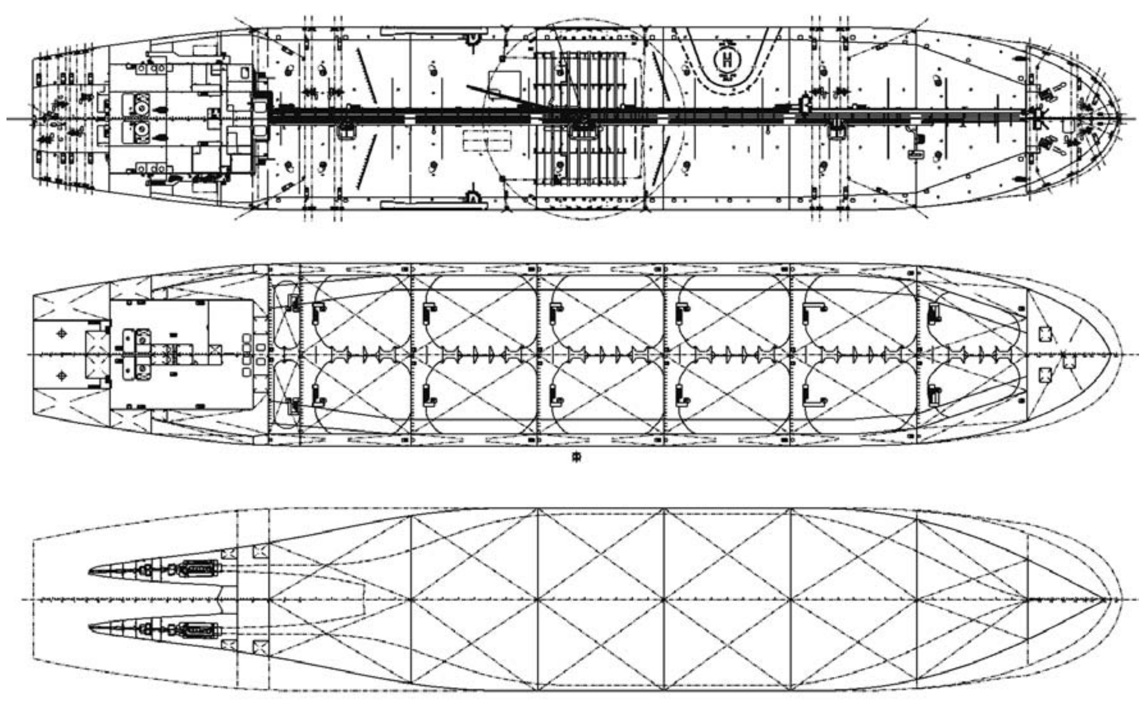


Fig. 2 Upper Deck Plan, In-Tank Plan and Plan on Tank Top

In all Polar committed about $600,000 to the hull design/model test program. This represents less than 0.2% of the cost of the original construction program, and less than 0.06% of the total cost for the five-ship program. If the improvement in efficiency is considered alone, there was a 6% improvement in speed/power from the initial design to the final testing. However, the gains from model testing were far more extensive. Of significance are; the use of a semi-balanced rudders, improved seakeeping, R2-S+ heavy weather compliance, minimization of smoke effects, verification of design models, and data for crew training at bridge simulators.

Resistance & Propulsion Design and Testing

Program

The Resistance & Propulsion portion of the Model Test Program was intended to optimize the overall hull performance of the *Polar Endeavour*. Historically, Polar's tankers were optimized based on still water conditions. Unfortunately, the waters in which they operate are rarely, if ever, "still". Polar believed that a thorough design program could produce a vessel that was not only efficient in "still" conditions, but that would also be efficient in the moderate to rough conditions normally experienced in the Gulf of Alaska. The program developed by Polar in conjunction with SSPA Maritime Consulting (SSPA) involved review of a preliminary (first generation) design, including a Computational Fluid Dynamics (CFD) optimization, and development of a set of second generation design along with testing. Review of the second-generation design and further modification as required produced a final (third generation) design.

As part of the initial design review SSPA questioned Polar's preference for MAN-B&W, 7S50MC-C slow speed diesel engines (11,060 KW @ 127 rpm). SSPA felt consideration needed to given to lowering engine rpm to 106, and using a larger diameter propeller. Polar chose the seven cylinder, 127 rpm engine for a number of reasons. Seven cylinders offered the best answer to vibration problems. Five cylinder engines have inherent problems, which both SSPA and the manufacturer recommended avoiding. Smaller cylinder size meant larger numbers of cylinders (8) and problems with matching cylinder numbers (8) with propeller blades (4). More cylinders also presented problems with engine room length. Larger cylinder size posed similar problems between numbers of cylinders (6) and propeller blades (4). The larger bore engines substituted length problems with breadth problems. It was more difficult to fit the wider engines into the gondolas. Another advantage to using the higher rpm engine was dealing with propeller tip immersion during heavy weather when the vessel is in ballast. The 127-rpm engines resulted in 5.8 m diameter propellers. This gives a 4.2 m immersion in ballast versus the 2.0 to 2.4 m immersion Polar has on other vessels.

Hull Form Design & CFD Optimization

SSPA, the contractor for hull design and model testing, was given an initial set of lines from which to start their design. This set of lines was developed during initial design studies. The initial lines represented a first attempt by hull designers at designing a 125,000 DWT, 16.0 m draft tanker with a total cargo cubic volume of 1,017,000 bbls. The initial design was for a twin gondola stern tanker with a parallel middle body of about 33% of the LBP. The initial design was never intended for use as a final design and it was recognized that further development was required. The only design restriction imposed on SSPA, by Polar, was a result of the arrangement gondolas on the initial design. The gondolas skewed outboard in such a manner that special cradles would be required for building and future dockings. SSPA was instructed to provide gondolas with a flat area that was in the same plane as the horizontal flat keel. This would permit docking with standard keel blocks under each gondola.

SSPA started with the initial lines, generated a new design and then developed a second design for the CFD portion of the study. SSPA's CFD investigation resulted in minor changes to the bow portion of the lines, and virtually no changes to the parallel mid-body. The CFD, along with Polar's requirements for modifying the gondola design, resulted in significant changes to the after body of the tanker. Figures 3 and 4 show the body plans for the initial design and SSPA's second design, respectively [1].[3] The end result was that both the original design and SSPA's design were good. The latter provided smaller static and dynamic wetted surface, smoother pressure distribution in the fore body, lower wave heights along the hull, and a smaller pressure difference between the inside and the outside of the skegs. The initial design had enough free board to keep the deck dry in operational conditions, and the bow flare was suitably shaped to minimize green water on deck. Bow flare slamming was predicted to be low even in storm conditions.

[3] Numbers in brackets refer to references at the end of the paper.

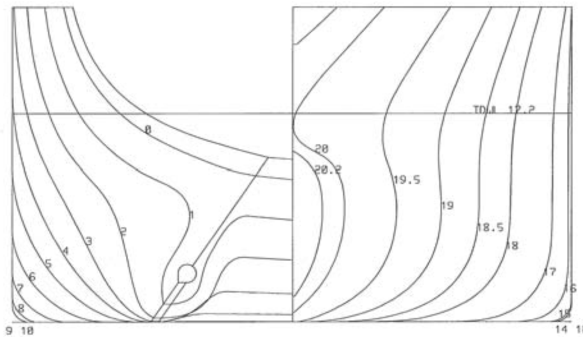


Fig. 3 Initial design - Body plan

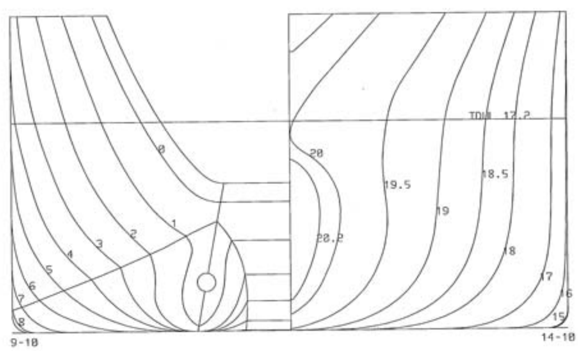


Fig. 4 SSPA second design - Body plan

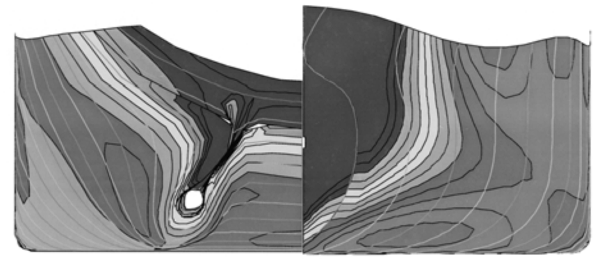


Fig. 5 Initial design - Flow and pressure distribution

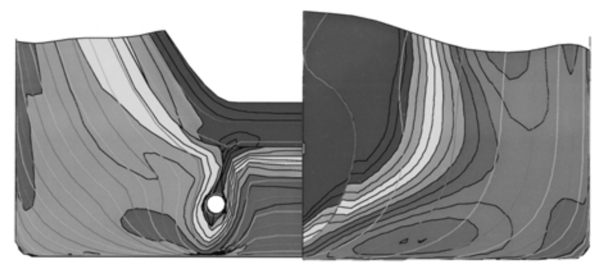


Fig. 6 SSPA second design - Flow and pressure distribution

Figures 5 and 6 show the improvements in flow and pressure distribution between the initial design and the second design from the CFD process [1].

Testing and Development of Hull Form

Resistance and propulsion testing was done first on the design produced from the CFD analysis, and then modifications were made to create the final hull form. SSPA conducted a full set of resistance and propulsion testing on the CFD hull form, Figure 6, including; resistance, propeller rotation (both inboard and outboard), rudder optimization, wake survey, streamline (paint) and self propulsion testing. Self-propulsion testing was done using library propellers. All testing was done using a 1:34.118 scale model. After completion of a first round of testing modifications were made to the hull and a second set of tests, with the exception of the streamline test, were conducted. Testing was conducted at both ballast (9.0 m fore/10.0 m aft) and design (16.0 m fore/aft) drafts.

In the initial testing SSPA found that, as compared to other vessels of similar dimensions and fullness, the resistance and propulsive qualities were "significantly better than average." Due to confidentiality agreements, SSPA compares performance based on a subjective rating system of significantly better than average, better than average, average, and below average. The propeller rotation optimization showed an 8% lower delivered power for inward turning propellers versus outward turning propellers. Optimizing the rudders at a 3° offset (aft edge to centerline) reduced the required delivered power by 300 KW (1.7%).

Two observations were made during the first round of testing. First, the flatness of the hull between the two gondolas aft would, in a following sea, make them susceptible to slamming. And second, there appeared to be a large amount of water being dragged behind the vessel. This was easily illustrated by placing a crumpled piece of paper off the transom. This paper followed the vessel for the length of the towing tank. SSPA felt by experience that this water, which was being dragged, contributed little, if any, to resistance. Wave patterns were found to be favorable and the bulbous bow, particularly in the loaded condition, worked very well.

The flow streamline tests in Figures 7 and 8 showed generally good results, with almost no cross flow over the skegs [3]. There was some tendency for flow separation in the aft body, Figure 8. The test showed that the 3° offset for the rudder placement was correct. The wake distribution, Figure 9, showed a peak at 180° (bottom side of the skeg) [3]. The wake was found to have very high velocities between 60° and 150° at the inner radii. It was noted that improvement was possible by making the skeg fuller in the after part of the skeg.

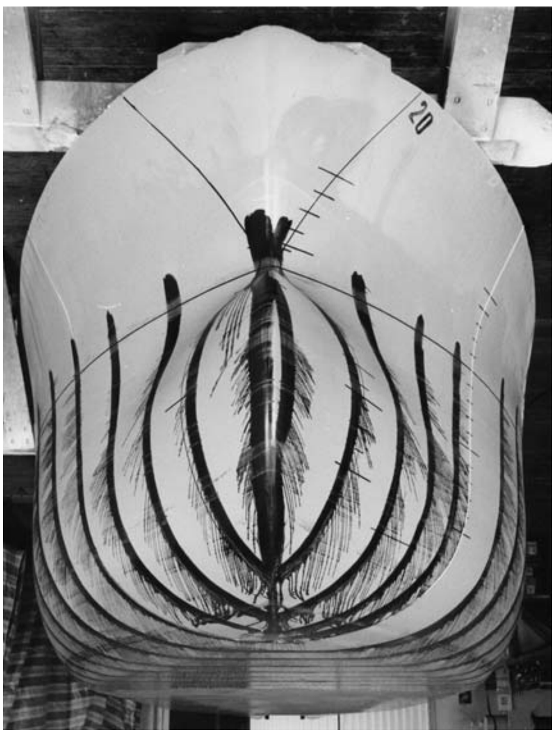


Fig. 7 Forebody streamline test

Work was being done concurrent to this portion of the model test program with regard to loading and compliance with trim and stability regulations. It was found in the full load, scantling draft condition that substantial ballast would have to be carried to compensate for excessive trim by the head due to the full volume of a twin gondola stern. Based on this information it was decided to revise the design and to run a second set of tests. The revision was to include; removing approximately 1150 m^3 of volume from the stern to produce a more favorable LCB, modifying the "flat" area between the gondolas to give it a "vee" shape to reduce effects of slamming from following seas, and to modify the after portion of the gondolas to improve wake distribution. No changes were made to the bow.

Fig. 8 Aft body streamline test

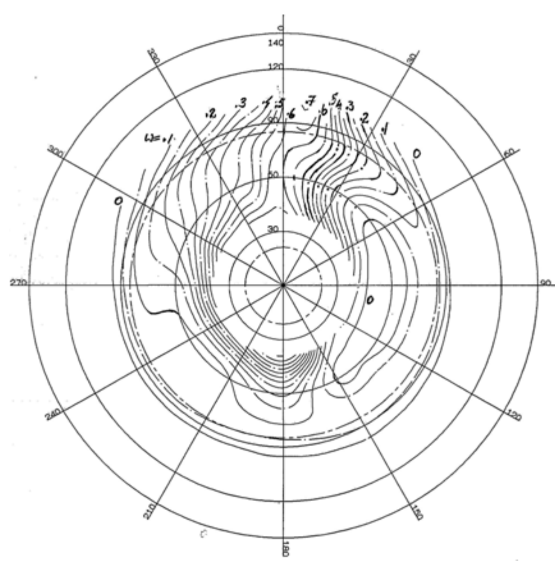


Fig. 9 SSPA second design - Wake distribution

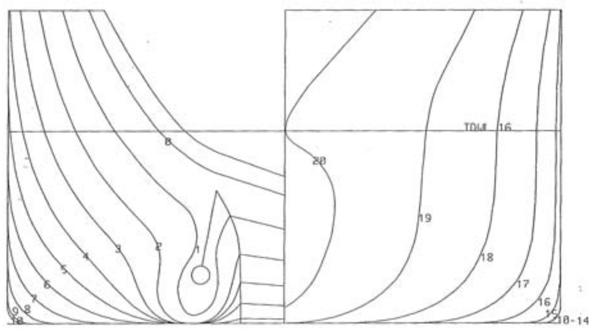


Fig. 10 SSPA final design - Body plan

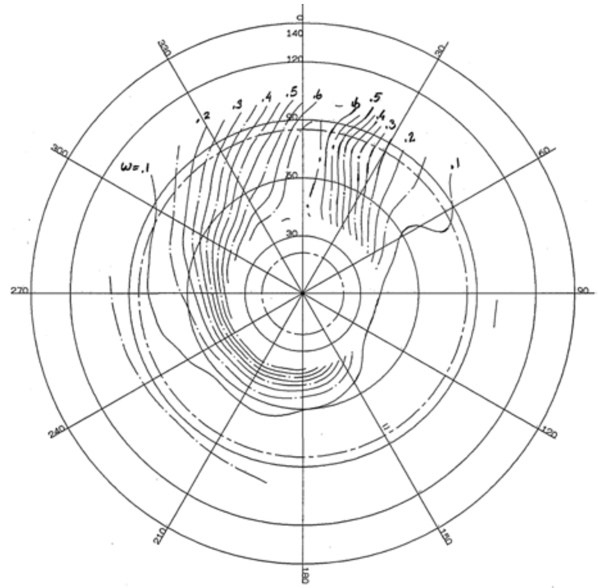


Fig. 11 SSPA final design - Wake distribution

Figure 10 shows the revised body plan for the second round of model testing [4]. This body plan, after confirmation of model testing became the final design plan. For this set of testing the library propellers were again used. Final model testing resulted in inward turning propellers with an 8% lower delivered power than with outward turning propellers. As before, it was found that a 3° offset for the rudders was correct. Figure 11 shows the wake distribution for modified stern [4]. It was found the wake distribution peaked at 180° and that the negative wake between 60° and 150° had been smoothed out. The water being dragged, although not felt to be contributory to resistance, was significantly reduced from the first set of testing. At this point in the test program, Polar and SSPA were satisfied that an optimum hull form had been achieved, and that further development was unwarranted.

Historically, Polar Tankers had less than favorable experiences using library propellers for final designs. While we recognized that design techniques allowed development of suitable designs, our comfort level was not sufficient to accept a design without testing. SSPA, after completion of the second round of testing was tasked with designing a specific propeller for the tankers and to conduct open water and self-propulsion testing. These same propellers were to be tested in SSPA's cavitation tunnel to assure suitable cavitation performance. It was recognized that the propeller designed by SSPA might not be the one recommended by the propeller manufacturer. Provisions were made in the Specification that if "major" changes were made to SSPA's design, they would be considered only if the manufacturer retested and showed equivalence to the performance demonstrated by SSPA.

In testing, cavitation and propeller noise was minimal; primarily do to small, high speed propellers and the accompanying tip clearances and propeller immersion. In all, at the 16.0 m design draft, there was a 0.25-knot increase in speed between SSPA's library and design propellers. The final design propeller tested about 0.05 knot less in speed, when compared to the SSPA design. This small difference between SSPA and Kamewa was attributed primarily to the application of Classification Society rules to the final design.

Hull Form Results

The end result of this portion of the model test program was an improvement in performance of between 7% and 10% from that predicted for the initial design to that of the final design. While it can be argued that it is unfair to make comparisons based on initial lines, from an Owner's perspective, it is not unusual for a shipyard, in their design process, to stop at the initial lines. The cost of the additional time spent in this portion of the design process is more than outweighed by the benefits.

Although it is a case of comparing apples and oranges, there is a tendency to compare the new ships to the ones they ultimately replaced. In comparison to the 120,000 DWT tankers that were in operation, the model testing was predicting an improvement of one knot in speed and a significant reduction in fuel consumption. The new ships are capable of carrying 125,000 DWT vs. the 120,000 DWT of their predecessors, they run a full knot faster, and they consume about 520 bbls/day of fuel as compared to 850 bbls/day. While it is recognized that much of the fuel savings comes from the switch from steam to diesel propulsion, much of the improvement is coming from improved hull efficiency. This improved efficiency is particularly noticeable in the ability to sustain operations in seaways for longer periods of time.

Seakeeping Testing

To Polar's knowledge, little work has been done in the past with respect to tankers and seakeeping. What work has been done has either been related to loading at offshore moorings and dynamic positioning, or was considered proprietary and was not readily shared by owners or model basins. As a result, real life performance, particularly of vessels engaged in the Alaskan trade, differed greatly from the calm water predictions from the shipyards. As a whole Polar's vessels, particularly in winter, suffered from wet to submerged decks, fatigue cracking as a result of cyclical wave loading, and slowing in speed due to seas. It was believed that a modest effort in the area of seakeeping would result in drier decks, reduced motions, and improved at sea performance. An added benefit was data collected would be used to support the structural design effort for the Dynamic Load Approach and the Structural Fatigue Analysis.

Program

SSPA and Polar embarked on a unique effort to both confirm the heavy weather characteristics of the vessel and to support the structural design efforts. The program consisted of two parts; first computer predictions of performance that would be used to develop the lines plans and second model testing to confirm the computer predictions and to provide real time data to the structural design effort.

Computer Predictions of Performance

SSPA used their SCORES computer program to make predictions of the vessels seakeeping characteristics. Using this program, they were able to make recommendations regarding bow flare and to modify bulb design to reduce immergence and to limit slamming. Their predictions indicated that the vessel would be drier than previous vessels, partially due to higher freeboard, and partially to better design. SSPA also encouraged, at this time, the addition of bilge keels to reduce rolling. This suggestion was not accepted because of bad experiences with structural cracking from bilge keels.

After completion of the seakeeping model tests, the computer program was again run to correlate the program to the model. In doing this, SSPA and Polar were able to cooperate in an iterative process, which enhanced data accuracy.

Model Testing in Seakeeping Basin

SSPA, at Polar's insistence, pushed their seakeeping testing in the model basin to its practical limits. First, to obtain data for structural design, Polar asked that pressure sensors be placed not only on the forecastle deck, upper deck, bow flare and forefoot, but that the model be cut amidships so that bending moments and shear forces could be measured. Polar also asked that the side of the vessel be fitted with a grid of pressure sensors so that a CFD model being used for structural design could be calibrated. These demands resulted in one of the most highly, if not the most highly, instrumented tanker models tested in SSPA's model basin.

SSPA recorded the following data during the seakeeping testing:

- Wave height
- Speed, rudder angle
- Thrust starboard propeller
- Thrust port propeller
- Number of revolutions, starboard propeller
- Number of revolutions port propeller
- Surge, sway, heave (re-calculated to the center of gravity)
- Roll, pitch, yaw
- Vertical bending moment amidships, L/2
- Vertical shear force amidships, L/2
- Horizontal bending moment amidships, L/2
- Relative motion station 1 starboard (station 0=AP), RM1
- Relative motion station 1 port, RM2
- Relative motion station 8 port, RM3
- Relative motion station 10 port, RM4
- Relative motion station 12 port, RM5
- Relative motion station bow, RM6
- Longitudinal x-acceleration at one location
- Lateral y-acceleration at two locations
- Vertical z-accelerations at three locations
- Slamming pressure with 5 pressure gauges, P1-P5
- Water pressure with 9 pressure gauges, P6-P14
- Water on deck with three gauges, G1-G3

All testing was done for both the loaded (Tf/Ta=16.0/16.0) and the ballast conditions (Tf/Ta=9.0/10.0). Tests were carried out on a 1:48.333 scale model in six different wave directions from 180 degrees (head waves) to 30 degrees. Tests were carried out for five different wave periods for each of the six headings at a ship speed of 15 knots. Tests were carried out for six headings in irregular waves from two perpendicular directions having a significant wave height of 4 meters and the cross direction having a significant wave height of 3 meters. The ship speed for the irregular waves was 14 knots. In irregular head waves (no cross waves) tests were also carried out in two storm conditions, significant wave heights of 9 meters and 13 meters at a ship speed of 5 knots.

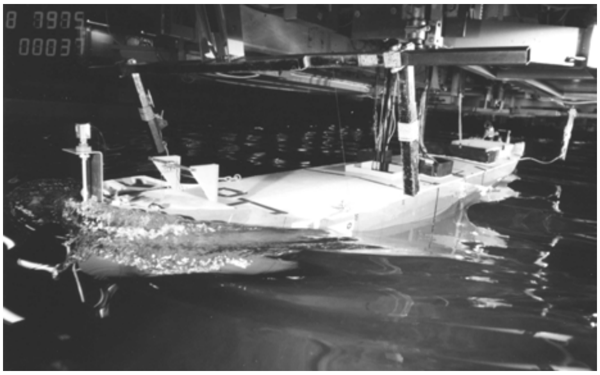
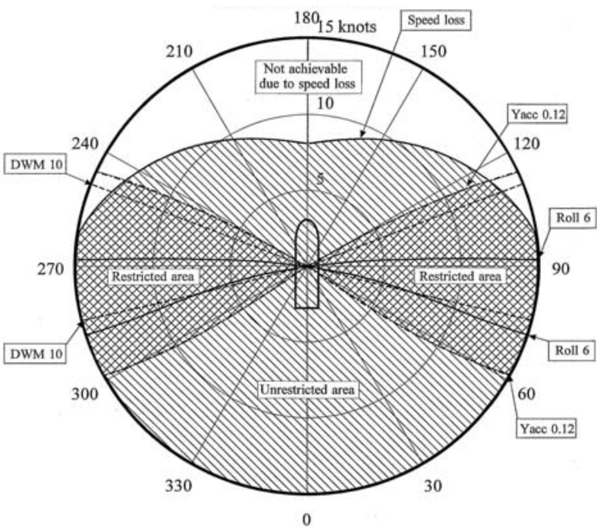


Fig. 12 Model testing ($H_{1/3}$= 9 m irregular head sea)



DW 10 = Deck wetness each 10th min (FP)
DWM 10 = Deck wetness each 10th min (L/2)
Roll 6 = Roll angle exceeds 6 deg (rms)
Zacc 0.10 = Vert. acc at FP exceeds 0.10 g (rms)
Yacc 0.12 = Lat. acc at bridge exceeds 0.12 g (rms)
VBM 115 = Vert. bend. mom. exceeds 115 000 tonm (rms)

Fig. 13 Operating curves for Full Load, Sea state 7

Figure 12 shows a $H_{1/3}$= 9m irregular head sea [9]. As can be seen from the photo, the deck and the forecastle are both dry. In comparison to our current ships we would expect to have large amounts of green water. In service we have found that the model predictions have been very accurate. The tests also showed that there should be little or no bottom slamming, which has been confirmed in service.

SSPA found that their measured and calculated wave-induced motions, accelerations, vertical bending moment, vertical shear force and added resistance in regular waves showed very good agreement for both loading cases.

The vessel displayed good course keeping in stern seas, wave directions 30 degrees and 60 degrees, for both loaded and ballast conditions in regular and irregular waves. In beam waves, wave direction 90 degrees, the following was observed especially for the full load condition: The tests in regular beam waves demonstrated that for waves with short periods there was a noticeable tendency to yaw into the waves. For long period waves there was a slight tendency to yaw away from the waves. There were some immediate periods with no marked tendency to yaw. The tests in irregular beam seas also revealed a tendency to yaw into the waves though less pronounced than the tendency observed in short regular waves. The ships have confirmed this tendency particularly when finding themselves in the trough of two waves.

The seakeeping testing provided exceptional data in support of the structural design work and in the effects of seas on the vessel. What wasn't clear was, how do we relate the information obtained in the model testing to the operators? Our vessels have long been fitted with a "Hull Monitoring System" provided by MCA Engineers as part of our Critical Area Inspection Program (CAIP) compliance. We use the hull monitoring systems on our vessels to monitor roll, pitch, acceleration, and bow immersion. Our goal is to reduce fatigue cracking by reducing the motions to which the vessel is exposed. To this end we approached SSPA about the possibility of presenting the seakeeping data in a format useable to the operator. What they proposed was an operability analysis, which would transfer the data to a user, friendly environment. Figure 13 shows the operating curves for the full load condition in a Sea State 7 [12]. The operator can look at the predominant wave direction, account for speed loss and determine the most suitable course. MCA has included these plots as part of the Hull Monitoring System so they are readily available to the operator on the bridge.

Results

The seakeeping studies at SSPA provided positive results consistent with Polar's desires. The *Endeavour* Class vessels perform better than previous vessels with regards to deck wetness, slamming, and the ability to maintain speed for longer periods of time, providing weather is not directly on the bow. On the other hand, crew complaints with regards to rolling are somewhat higher than expected, although not unanticipated.

The ability to use the model test data to support structural design was very significant. The data was used to confirm the CFD analysis used for the Dynamic Load Approach and in the Spectral Fatigue Analysis. Data was also used to confirm shear force and bending moment predictions.

Unanticipated was the useful data obtained in way of the operability analysis. While naval architects have long understood the effects of cyclic loadings on ships, and ship's crews have long understood the effects of sea state and direction on comfort, finding a common discussion point was problematic. The operability analysis has provided the naval architect a means for illustrating information on vessel motions. This information, which is intuitively obvious to the senior officer based on their experiences and training, can then be conveyed to junior officers as part of their training. To make the information readily available, the operability plots are included as screens on the vessel's Hull Monitoring System, which measures roll, pitch, acceleration and bow immersion. Junior officers have quick access to information on direction to alter course to minimize vessel motions.

It should be noted that while providing an operator with additional information on seakeeping of the vessel is important, it does not substitute for their experience. These plots are a useful training aid for experienced Masters to teach junior Mates. We find them to be only a reference to the senior Masters.

Maneuvering Computer Design & Model Testing

Background

Having made the decision to build twin-screw, twin rudder tankers, improved maneuverability was an inherent benefit when compared to the existing single screw vessels in Polar's fleet. However, decisions still had to be made with regards to enhanced maneuverability and just how much enhancement was required. It was determined quickly that there was no need, short or long term, to fit the *Endeavour* Class vessels for dynamic positioning. Therefore there was no need for multiple thrusters fore and aft. However, decisions still needed to be made as to whether a bow thruster would be fitted, and whether high lift rudders would be utilized.

Polar's senior officers wanted the ability to be able to dock and undock a vessel without tug assistance. Although it was never intended to eliminate docking tugs, the officers felt that it was advantageous to be able to fully control the movement of the vessel on and off the docks from the vessel's bridge. They wanted the new vessels to have the ability to move sideways and at angles, as desired. It was determined that tugs would always be used when winds reached 30 knots, so there was no need to supply thrusters for conditions greater than 25 knots. The officers also wanted the ability to have greater rudder control for maneuvering in port and during transits through Prince William and Puget Sounds.

Because these vessels were new to the Polar fleet and to U.S. shipping in general, Polar also felt a need to be able to acquire enough maneuvering data through computer simulation and model testing to allow the construction of accurate bridge simulation programs. This would allow officers to be thoroughly trained in ship handling prior to having ever set foot on a new vessel. This portion of the model test program provided necessary data to allow Polar's officers and port pilots to be trained in advance of the arrival of the *Polar Endeavour* on the West Coast. In general, since putting the vessel in service the officers have found it to be slightly more responsive than the initial simulator models predicted. These models have since been adjusted and now portray accurate representations for ship handling. A scale model of the ship has also been built for training at Warsash, based on the modeling information, to aid in ship handling training.

Computer Simulation

Computer simulations were used to assist Polar in selection of rudder type and size, range of rudder movement, and in sizing the bow thruster. To ensure an objective point of comparison in selection between alternatives, maneuverability projections were made against single screw tankers and IMO Resolution A.751. Prior to the start of testing Polar had interest in fitting conventional Mariner rudders, primarily because of simplicity and past experience. There was a high comfort level increasing the size of the rudders and allowing rudder movement to increase from the normal 35° to 35°, to 45° to 45°, providing that rudder movement was limited to 35° at speeds over 12 knots.

Table 2 shows a comparison of rudder sizes used in the study [2]. The total rudder area ultimately used was 3.66% of LppT. The difference in the original 3.03% and the final 3.66% was in the modification of the stern from the initial to final lines.

The computer simulations focused on turning and zigzag tests. Comparisons were made in normal conditions and assuming a single rudder failure to determine ability to meet IMO criteria in a disabled condition. All simulations were done using SSPA's PORTSIM simulation program. Tables 3 and 4 show the results of the simulations for turning circles and zigzags in normal operations [2].

Table 2 – Comparison of rudder sizes used in study

Ship	1	2	3
Stern Type	Twin Screw	Twin Screw	Single Screw
Rudder Type	Conventional Mariner	High Lift	Conventional Mariner
Rudder area, moveable [m^2/rudder]	60.8	44.9	89.8

Rudder area, total [m^2/rudder]	78.6	55.8	111.6
Height [m]	10.5	9.0	12.8
Total Area [% of LppT]	3.03	2.24*	2.24*

**Based on SSPA formula for minimum recommended area (% of LppT) = CbB/T*

Table 3 - Turning tests, Study ships vs. IMO requirements
Approach speed = 16 knots
35° rudder

	IMO	Ship 1	Ship 2	Ship 3
Advance/Lpp	4.5	2.18	2.00	2.22
Tactical Diameter/Lpp	5.0	2.47	2.20	2.20

Table 4 - Zigzag tests
Approach speed = 16 knots

	IMO	Ship 1	Ship 2	Ship 3
10°/10° Zigzag				
Initial Turning Ability / Lpp	2.5	0.99	0.91	1.08
1st Overshoot (°)	20	6.2	6.6	8.7
2nd Overshoot (°)	35	8.2	8.7	16.6
20°/20° Zigzag				
1st Overshoot (°)	25.0	13.0	14.3	17.9
2nd Overshoot (°)	n/a	13.5	14.3	21.5

As indicated, both the conventional Mariner rudder and the high lift rudder produce results that are significantly better than the IMO requirements and that are better than a comparable single screw vessel. Based on the computer predictions, Polar's knowledge of Mariner rudders, and no requirement for dynamic positioning, it was determined best to proceed using oversized Mariner rudders.

As part of the performance evaluation simulations were made for disabled conditions. Predictions were made assuming one of the rudders failed. As can be seen from the data, the *Endeavour* Class tankers should meet IMO maneuverability requirements even with a single failed rudder and a failed propeller. Tables 5 and 6 show the results of the simulations for turning circles and zigzags, under starboard single screw operation [2]. These results were later updated when the R2-S+ testing was done. However, rather than upgrade the tables, operability plots were developed.

For the purpose of the computer simulations it was assumed that a single 2800 KW tunnel thruster of 3.0 m diameter and an anti-suction tunnel would be installed forward to produce 360 kN maximum thrust. This provided an ability to crab laterally at 0.5 knots against a 25-knot wind, with a 2-knot current running along the length of the vessel. In order to turn the ship 90° at ballast draft in about 500 seconds a 2207 KW (3000 HP) thruster was determined to be required. Ultimately a 2207 KW thruster of 2.4 m diameter with a 0.8 m diameter anti-suction tunnel were fitted.

Model Testing

Free sailing model tests were carried out in order to study the maneuvering characteristics in general, and with respect to IMO Resolution A.751 in particular. The 1:48.333 scale model used for the seakeeping testing was also used for the maneuvering tests. Turning tests to port and starboard at 35°, zigzag tests at 10°/10° and 20°/20° with 1st execute to port and starboard, and reverse spiral tests for both full load and ballast conditions were conducted. Table 7 shows the maneuvering characteristics for the *Endeavour* Class tankers in their final design configuration [8].

IMO stopping ability was not tested during the maneuvering tests.

Results

Because there was no intent to dynamic position the *Endeavour* Class vessels it was decided that oversized Mariner rudders were a better solution than high lift rudders. The final rudders were approximately 35% larger than what is considered normal for rudders on a vessel of this size. As a means of limiting loading on the rudders an electronic limit was installed which limits rudder movements to 35° at speeds 12 knots and above and allows the rudders to go to 45° at speeds below 12 knots.

It was determined between the wind tunnel testing and the maneuvering testing that a 2207 KW (3000 HP) bow thruster would be used. This thruster would be capable of turning the vessel in a 25 knot wind, and would have the capabilities to work in unison with the twin screws and twin rudders to allow sidewise motion of the vessel at low and zero speeds.

Table 5 - Turning tests in a disabled condition
Approach speed = 11.5 knots
35° rudder

	IMO	Ship 1 Port/Stbd	Ship 2 Port/Stbd
Advance/Lpp	4.5	2.59/3.14	2.37/2.87
Tactical Diameter/Lpp	5.0	3.04/3.78	2.75/3.33

Table 6 - Zigzag tests in a disabled condition
Approach speed = 11.5 knots

	IMO	Ship 1 Port/Stbd	Ship 2 Port/Stbd
10°/10° Zigzag			
Initial Turning Ability / Lpp	2.5	1.31/1.34	1.16/1.24
1st Overshoot (°)	20	5.5/5.1	5.35/5.5
2nd Overshoot (°)	35	6.4/9.9	6.9/9.0
20°/20° Zigzag			
1st Overshoot (°)	25.0	11.3/8.8	11.4/9.4
2nd Overshoot (°)	n/a	9.5/13.6	10.3/13.2

Table 7 – Final maneuvering characteristics

	IMO	*Endeavour* Class
Turning Test 35°		
Advance/Lpp	4.5	3.19
Tactical diameter/Lpp	5.0	3.21
Zigzag Test 10/10°		
ITA/Lpp	2.5	1.55
1st overshoot [deg]	20	5.9
2nd overshoot [deg]	35	8.6
Zigzag Test 20/20°		
1st overshoot [deg]	25	11.8
2nd overshoot [deg]	n/a	9.8

Performance

The ultimate goal was for the vessels to exceed the IMO requirements for maneuverability, to be able to crab on and off docks under their own power, and to be able to turn at zero speed in their own length. These goals were based on the concept that the vessels would be highly maneuverable at sea, when maneuvering, and when docking. This goal was achieved based on computer predictions, model basin testing, full scale testing, and most importantly in service. The *Endeavour* Class vessels maneuvering capabilities closely match those predicted in computer and model testing. Since their introduction, the vessels continue to have tugs secured, but they dock and undock under their own power and control. They can turn, at zero speed, in their own length.

Propeller Design & Cavitation Testing

Background

Polar relied historically on the shipyards for hull and, subsequently, for propeller design. After some unexpected propeller problems on one class of vessels, it was discovered that the shipyard and the model basin had decided, together, to forego any specific propeller design and instead to use a library propeller as a "good enough" fit. Later in the life of the vessel this caused both performance and cavitation problems, both of which could have been avoided. Polar required that propeller design and cavitation studies be done to ensure that the *Endeavour* Class vessels had propellers that were "optimized" within the design limits of the engines and hulls. SSPA started with a "best" selection from their propeller library, tested with the model, then designed a specific propeller for the *Endeavour*. The designed propeller was tested with the final hull design and was cavitation tunnel tested to ensure performance. Propeller manufacturers were allowed to either accept the SSPA design, or modify the design, under the provision that any significant change would require a return to SSPA to repeat performance and cavitation tests.

Program

The initial test program consisted of open water testing to confirm the performance of the library propeller and then resistance and propulsion testing using the library propeller. Based on these results, along with the wake surveys, a specific design propeller was provided by SSPA. SSPA was not constrained in design, other than an owner's constraint limiting back skew to 35°, and a requirement to meet ABS Rules.

Library Propeller

Figure 14 shows the open water curve for the library propeller [3]. The library propellers alone provided satisfactory results. However, both SSPA and Polar were confident that improvements in efficiency and noise could be achieved by using a specifically designed propeller.

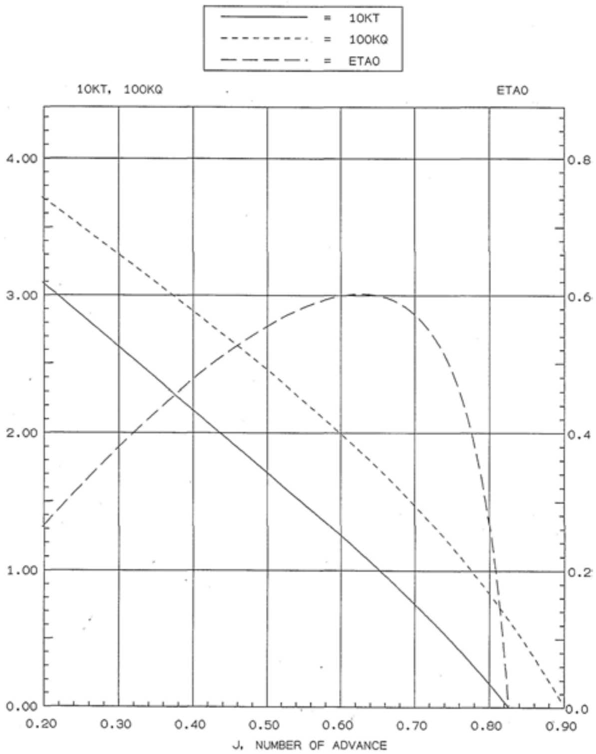


Fig. 14 Open water curve for library propeller

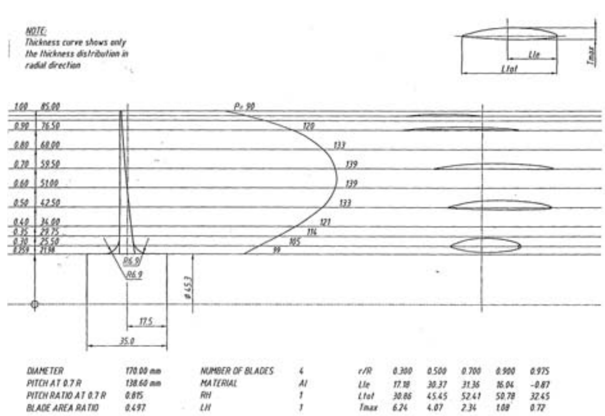


Fig. 15 SSPA propeller design

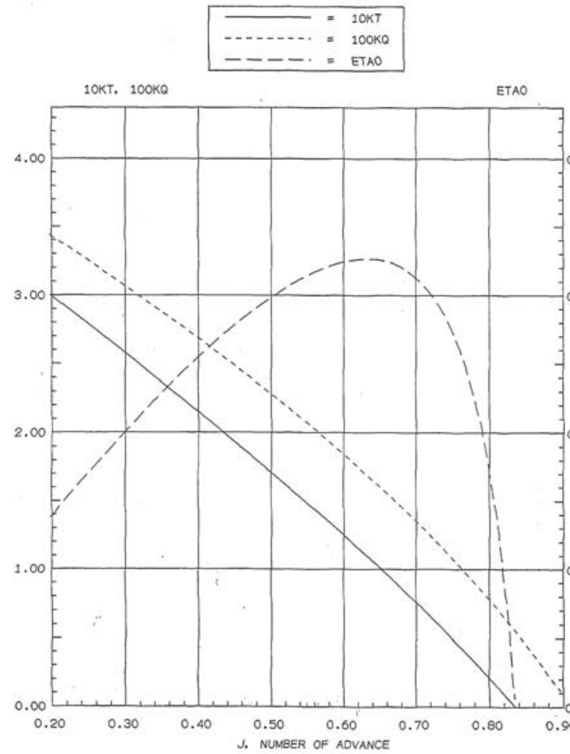


Fig. 16 Open Water Curve for SSPA Propeller

SSPA Propeller Design & Testing

In designing a specific propeller for the *Endeavour* Class vessels, SSPA again approached Polar about their constraints. Polar again reiterated their desire to retain propeller speed at 127 rpm. In discussing Polar's somewhat arbitrary decision to limit back skew to 35°, SSPA indicated that they felt no need to use higher skews. Polar's reluctance to increase skew angle was based primarily on inexperience. Unlike passenger or naval vessels where noise is of significance, tanker owners worry more about reliability and maintainability then comfort.

Open Water

Figure 15 shows the SSPA designed propeller [5]. The back skew angle selected by SSPA was about 25°. Figure 16 shows the open water curve for the SSPA design propeller [5]. The new propellers showed a 2.5% improvement in efficiency over the library propellers.

Cavitation Tunnel

Cavitation tunnel testing was done using SSPA's large cavitation tunnel. Because of the higher propeller speed (127-rpm), the smaller diameter (5.8 m), and the high tip clearance (4.2 m in ballast) very good performance was expected. Not surprisingly, excellent performance resulted. Cavitation observation tests were done at two loading conditions, equivalent to 90% MCR at 14 knots at full load draft and 15 knots at ballast draft. This is equivalent to a sea margin of 70%. The predicted vibration velocity at blade frequency using SSPA's empirical method was about 0.75 mm/s at full load and about 2.1 mm/s at ballast draft. According to SSPA this is a very conservative estimate. The ISO6954 norm regards vibration velocities of less than 2.2 mm/s as fully acceptable.

Kamewa Propeller Design & Testing

Having been awarded the contract to supply propellers for the *Endeavour* Class vessels, Kamewa was given an option to accept the SSPA design, or to offer an alternative design. On review of the provided design Kamewa discovered that adjustments had to be made for compliance with ABS Rules to meet specific design particulars. Most of these adjustments were associated with requirements for blade root strength and thickness. Kamewa also initially approached Polar with a proposal to increase back skew above 35° in hopes of recovering some performance losses resulting from changes to blade root thickness. Ultimately, Kamewa found that a 33° back skew was consistent with their optimum.

Figure 17 shows the final Kamewa designed propeller, with a back skew angle of about 33° [19]. Figure 18 shows the open water characteristics for the Kamewa propeller in comparison to the SSPA propeller [19]. As can be seen from the two curves the two propellers are extremely close in performance, but both are better than the library propeller.

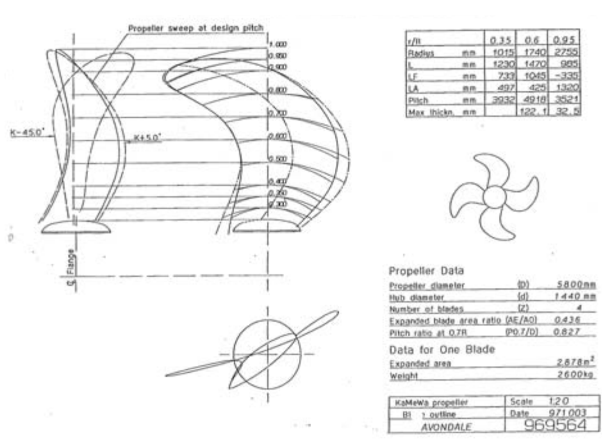


Fig. 17 Kamewa design propeller

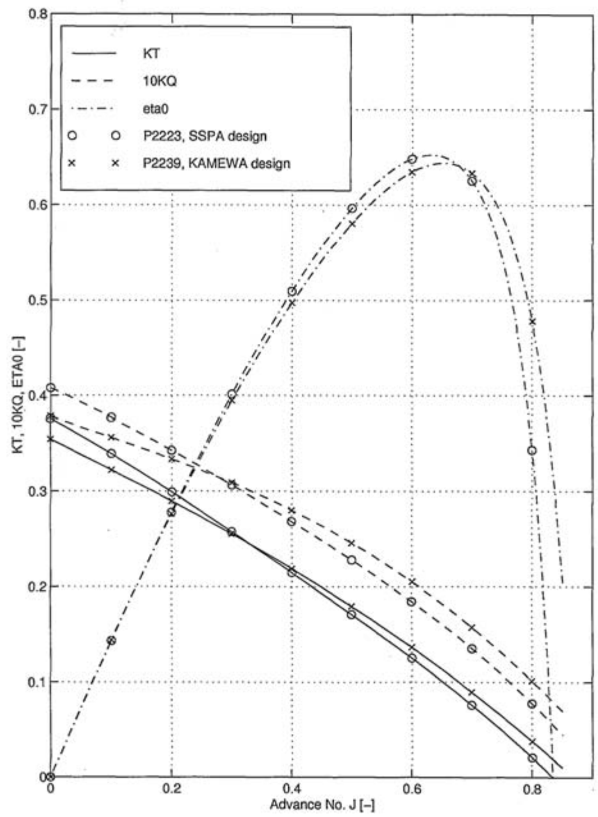


Fig. 18 Propeller comparison - Kamewa vs. SSPA

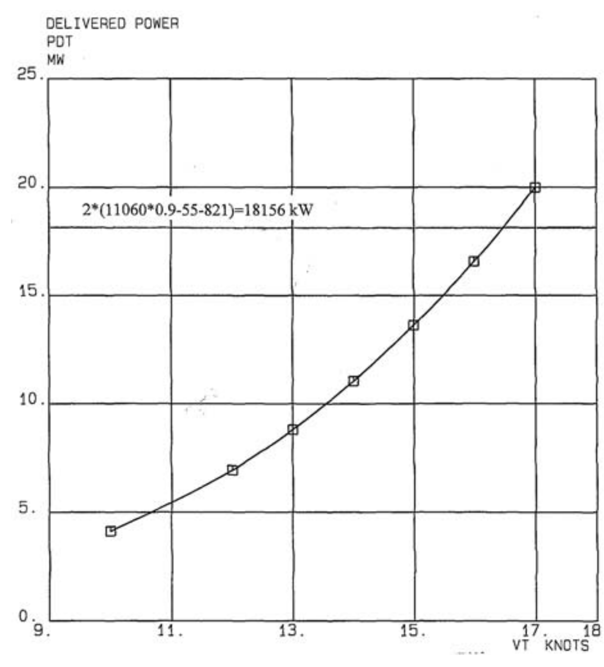


Fig. 19 Final speed-power curve for *Endeavour* Class tankers

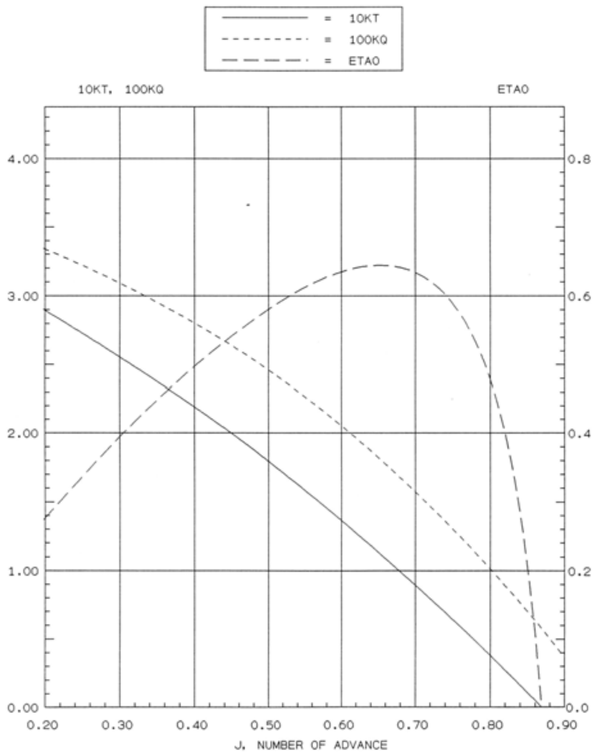


Fig. 20 Final Kamewa propeller curves

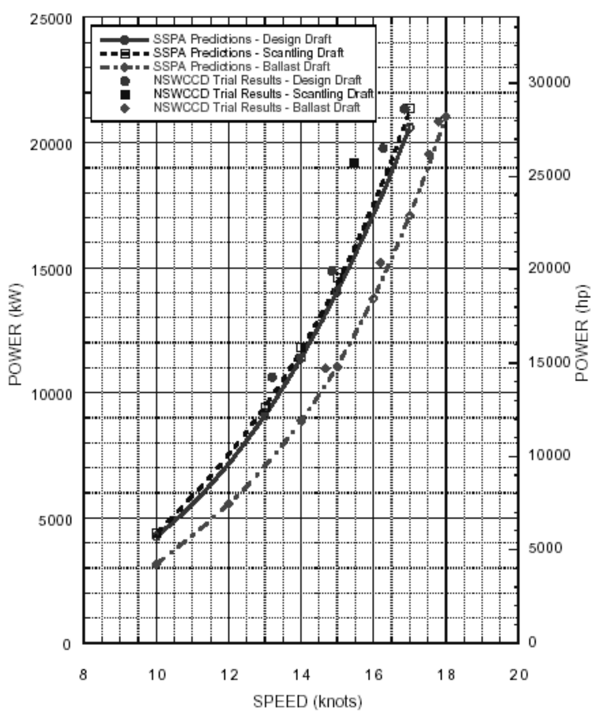


Fig. 21 Sea trials results – SSPA predictions vs. sea trials data

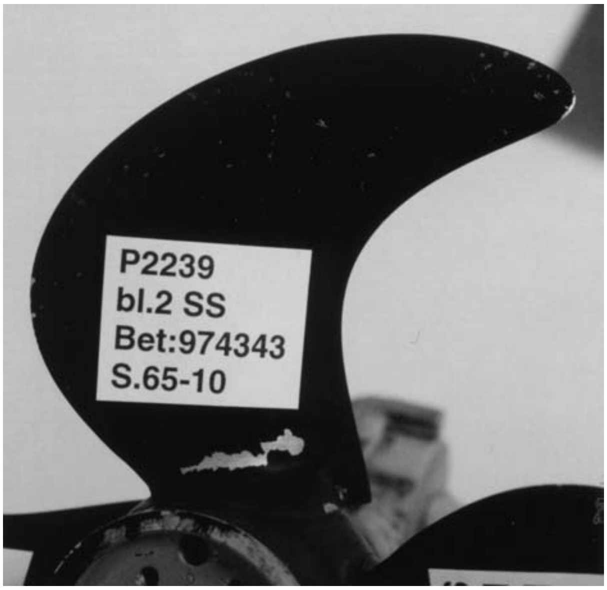


Fig. 22 Cavitation Test Results

Open Water

Figure 19 shows the final speed power curve for the *Endeavour* Class tankers [19]. Figure 20 shows the open water curve for the selected propellers [19]. Although there was a slight decrease in performance between SSPA's propellers and Kamewa's due to blade root thickness, the difference was within measurement accuracies. Figure 21 shows the results from Sea Trials [26]. It should be noted that the Sea Trial testing was somewhat clouded by currents and poor weather.

Cavitation Tunnel

Like the SSPA designed propellers, the Kamewa propellers performed superbly in the cavitation tunnel. Cavitation observation tests were done at two loading conditions, equivalent to 90% MCR at 14 knots at full load draft and 15 knots at ballast draft. This is equivalent to a sea margin of 70%. The predicted vibration velocity at blade frequency according to SSPA's empirical method was about 0.72 mm/s at full load and about 2.1 mm/s at ballast draft. This according to SSPA is a very conservative estimate. No vibration problems were anticipated due to values measured pressure pulses. Figure 22 shows the impact of cavitation on the propeller [20]. The loss of paint near the blade root was from handling versus cavitation.

Results

The final propeller design resulted in propellers that met Polar's expectations and that will provide excellent performance. Although having a moderate back skew of only 33°, it is still a very large amount for most tankers. Cavitation tunnel results predicted negligible cavitation and propeller-induced noise. To date there have only been diver inspections of the propellers but there have been no reports of any damage of any kind. We have had no reports of any cavitation noise or propeller-induced vibrations from the crew.

Wind Tunnel Testing

Program

Unusual to tanker design are wind tunnel tests. In general, the design of tankers does not require information provided by wind tunnel studies. Stack heights are generally high enough that smoke problems rarely exist. Information on wind loads is useful, but there are other suitable ways to predict loading.

The Carquinez Bridge in the San Francisco Bay area limits the air draft of large tankers. The air draft in effect limits the height of the radar scanners. This in turn limits stack height to ensure there are no blind spots on the radar screens. Based on experiences with the design of Polar's 190,000 DWT vessels we knew this process resulted in smoke problems on the stern of the vessel. Similar hull depths, and requirements for bridge visibility that results in higher bridge heights, led us to believe we would encounter similar problems on the *Endeavour* Class vessels. These factors led to a decision to do testing, recognizing we could only reduce, but not eliminate smoke problems. It was also decided that if we were to do testing it would be a good opportunity to validate wind force data.

Another issue associated with current tanker design is the affect of bunker tank vent locations on the intake of fumes and odors into the accommodation block ventilation system. This problem has recently been exacerbated by recent SOLAS rules, which require raising bunker tank vents above the upper deck level to prevent accidental down flooding by boarding seas.

Stack Gas Trajectories

As expected, the early design configuration shown in Figure 23 provided results that were less than satisfactory. Smoke tests indicated that a large amount of smoke would be drawn into the dead area immediately aft of the house and forward of the stack and onto the after deck area of the stern. Using a 1:250 scale model for the testing, shown in Figure 24, the first efforts were made to modify the configuration of the exhaust pipes coming from the stack [10]. Angled pipes replaced straight pipes. Various angles from vertical were tried, including angling the stacks off centerline. Angled pipes worked much better than straight pipes, but the farther off centerline the pipes were placed the worse the performance became.

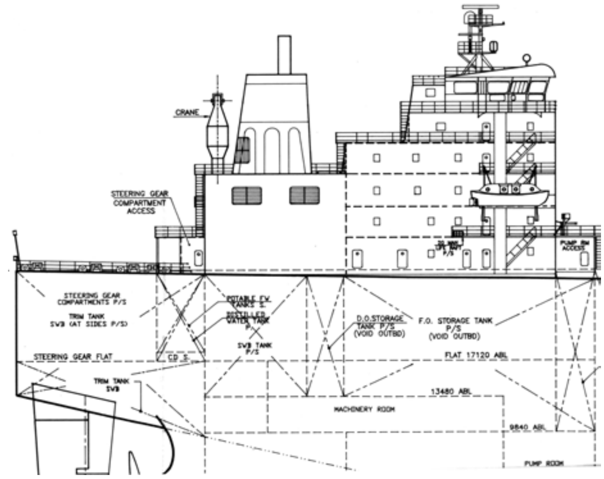


Fig. 23 Original house and stack configuration

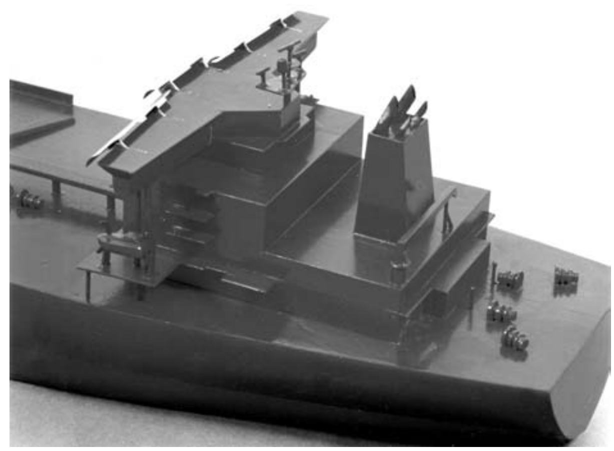


Fig. 24 Scale model used in wind tunnel testing

While this process provided improvement, on a relative scale improvement was from very poor to poor. Further improvement was needed. At this point SSPA, based on previous experience, and the author, who was involved in similar tests done years earlier, concluded that some form of foil was needed on the house top to modify the airflow to the stack. Polar's 190 MDWT tankers were fitted with a radiused leading edge on the wheelhouse, and a foil about 1 m above the house top. In the case of the *Endeavour* Class vessels the wheelhouse is fully enclosed from the centerline to the bridge wings. SSPA, based on previous experience, recommended not putting a radius on the leading edge of the house front, but instead extending the wings for the full width of the enclosed bridge. These modifications were made with an improvement in the amount of smoke being kept between the stack and house and on the after deck. While not perfect, the improvement could be rated on a relative basis from poor to fair/good. Short of raising the stack 6 m, good to excellent performance was not possible.

Wind Load Testing

Testing for wind loads was done in both ballast and loaded conditions. The tests provided no new information over that found in numerous publications. The tests served only to provide measured versus calculated values for wind loading. This data was used to aid in mooring studies and in the sizing of the bow thruster. The data did confirm existing data as being accurate.

Ventilation Intakes

Eliminating fumes and odors from bunkers and lubricating oil vents will likely be a problem for vessels under the new SOLAS rules for vent locations. As a rule of thumb the accommodation block air intakes should be above and away from vents. This, of course, is easier said then done. Rules push the vents to the "B" (third) deck level, and intakes higher. Because the SOLAS rules had not yet been promulgated at the time the initial design was being done for the *Endeavour* Class, no effort was made to raise the air intakes from their original positions immediately below the "A" deck level (galley and wheelhouse intake), and on the "B" deck (accommodation block intake) between the house and the stack. The accommodation ventilation intake was far enough away to ensure that no fume or vapors would be drawn into the house. The same could not be said for the galley and wheelhouse intakes. It was virtually impossible to locate the intakes far enough away from any vent to ensure that no fumes would be drawn into the house. Rather than redesigning the accommodation block, it was decided best to place intakes port and starboard to allow one side to be secured when fuel or lubes were being transferred on that side.

Results

The wind tunnel testing proved to be very accurate in its predictions. Air foil angle was set to an "optimum" based on subjective nighttime sea trial observations. A determination was made as to when the least amount of smoke was present over the after deck and between the house and stack. In service, smoke is drawn into the area between the house and stack and affects the afterdeck. However, smoke is no worse than expected. In the case of the air intakes, the starboard side air intakes were eliminated as part of the yard's design process. Unfortunately, this also eliminated the ability to select the side air was being drawn into the galley and the wheelhouse. This has proven to be a design error. Bunker fumes have plagued the *Polar Endeavour* since she entered service. This problem has been resolved on later ships by raising the wheelhouse and galley vent intakes through the "A"-Deck platform to provide a distinct isolation. Since this correction has been made the complaints have disappeared.

Disabled Ship Testing

Program

The Disabled Ship Testing program provided perhaps the most unique and creative portion of the model test program. Up until that point in time, analysis of disabled ships was limited to drifting studies and some computer simulations to predict performance of twin screw/twin rudder ships in disabled conditions. Being the first ship to seek compliance with ABS R2-S+ requirements, computer simulations were required for the first time to prove vessel capabilities. ABS was concerned how accurate computer simulations were, however, and if they were truly indicative of the vessel performance. After long discussions between Polar and ABS, and Polar and SSPA it was determined feasible to return to the model basin using the maneuvering model to verify the computer model. In addition, a unique opportunity occurred during sea trials to test disabled performance capabilities in Sea State 6 conditions. This furthered knowledge of disabled ship performance.

Computer Simulations

Compliance for the ABS R2-S certification requires:

"A vessel fitted with multiple propulsors (hence multiple propulsion systems) which has the propulsion machines and propulsors, and associated steering systems arranged in separate spaces (propulsion machinery space and steering gear flat) such that a fire or flood in one space would not affect the propulsion machine(s) and propulsor(s), and associated steering systems in the other space(s) will be assigned the class notation R2-S [27]*."*

For the plus (+) notation;

"Upon a single failure, the propulsion and steering system is to be continuously maintained or immediately restored within 2 minutes, as in the case when an alternate standby type of propulsion is provided (e.g., electric motor, diesel engine, water-jet propulsion, etc.) such that the vessel is capable of maneuvering into an orientation of least resistance to the weather, and once in that maintaining position such that the vessel will not drift for at least 36 hours. Using all available propulsion and steering systems including thrusters, if provided may achieve this. This is to be possible in all weather conditions up to a wind speed of 17 m/s (33 knots) and significant wave height of 4.5 m (15 ft.) with 7.3 seconds mean period, both of which are acting

concurrently in the same direction. The severest loading condition for vessel's maneuverability is also to be considered for compliance with this weather condition [27].*"*

These weather conditions are approximately equivalent to a Sea State 6 or Beaufort 8 sea.

SSPA, using their Portsim simulation program, was able to provide computer predictions for single failures required under R2-S+, and also multiple failures, i.e., rudder and propeller, and two rudders. Portsim predicted compliance, however ABS had no basis to determine the accuracy of the computer predictions. Because we could not provide correlation data for disabled conditions, we reached agreement with ABS to do disabled model testing. Once this model testing was complete, it was agreed that the Portsim model would be updated to reflect the model data. Of particular interest in the Portsim predictions was that it was easier for the vessel to proceed en route than it was to hold station per ABS R2-S+ requirement. When asked, ABS agreed that proceeding under control to the vessel's destination satisfied their requirement for holding station.

Model Test Confirmation

A full series of model tests were performed to validate the Portsim model. These tests were designed to study the behavior of the vessel in various failed conditions. For single failures, model tests were carried out either with one propeller free-wheeling (wind-milling) at design pitch or with one rudder locked amidships. For multiple failures, model tests were carried out with either one propeller free-wheeling at design pitch and a rudder locked amidships, or with a propeller free-wheeling at zero pitch and the rudder locked hard over at 45°. The tests were carried out at two sea states with long-crested irregular waves and steady wind. Table 8 lists the maneuvering test criteria used [21].

Course-keeping and steering tests were run to determine minimum speed to maintain heading and maximum attainable speed. Drifting tests were also conducted to supplement the **Disabled Tankers Report of Studies on Ship Drift and Towage,** published by the Oil Companies International Marine Forum [28].

Table 8 - Maneuvering Test Criteria for R2-S+

Sea State	Sine wave height (m)	Zero Crossing Period (sec.)	Mean Wind Velocity (m/s)
4	1.9	6.3	9.8
6	5.0	8.8	19.3

Sea Trials

Polar intended from the very beginning to verify the results of disabled vessel testing during sea trials. It was intended, as with any sea trial, to perform a series of tests in calm weather conditions that could be extrapolated to heavy weather conditions. During trials, rather than having calm conditions at the time disabled vessel testing was to occur, there were Sea State 6 conditions. To facilitate testing, and to obtain the most useable data, it was decided the best way to acquire that data was to have the vessel perform 10°/10° and 20°/20° zigzags at increasing 30° heading increments until the compass rose was boxed. One propeller was set to zero pitch and was allowed to freewheel, and the corresponding rudder was locked hard over at 45°. Except for one 10°/10° maneuver, the vessel was able to maintain steerage and headway. In the case of the one maneuver, the vessel went into "irons" (i.e., lacked sufficient speed and stopped) and it had to wait until it naturally came back into the wind before control could be regained. This result was consistent with predictions from Portsim.

Results

The data acquired during the Disabled Ship Testing portion of the design provided some interesting problems for SSPA and Polar. The ship outperformed either SSPA's or Polar's expectations. In fact, the performance was so good that a device for transferring the information to ship's crews had to be developed.

The *Endeavour* Class vessels satisfied the ABS R2-S+ requirements for single failures in Sea State 6. Fig 25 and 26 show the polar plots for single failures (i.e., propeller or rudder) in a Sea State 6 as required for compliance for R2-S+ [22]. As can be seen from the figures it is more difficult for the vessels to maintain position than it is for them to proceed to their destinations. In neither the loaded, nor the ballast case, do the vessels, after a single failure, encounter any difficulties proceeding. The inner ring of the "donut" is the minimum speed for the vessel to maintain steerage. The outer ring is the maximum speed attainable. As can be seen, single failure compliance is attainable.

Further to the single failures was the question of multiple failures. Fig 27 and 28 show the polar plots for multiple failures (i.e., propeller and rudder) in a Sea State 6 [21]. As can be seen, it is still possible to control the vessel, however, the ship's crew must be aware of limitations and must avoid certain "dead" areas where the ship could go into "irons". The "donut" reduces to a "C" in the area from 30° to 90°. It was in this region that during sea trials steering control of the vessel was lost during the 10°/10° maneuver. During the 20°/20° maneuver for the same failure steering control was maintained.

To provide the ship's crews with this data in a useable and understandable format it was decided to develop a supplement to well known publication **Peril at Sea and Salvage, A Guide for Masters** [29]. For this document to be useful it had to present the work done by naval architects at SSPA in a form known and useable to ship's personnel. Working with SSPA a stand-alone supplement was written. This supplement provides polar plots along with written explanation. Using "Peril at Sea" and the Supplement the ship's officers have enough data at hand to respond to single and multiple failures.

HULL STRUCTURAL DESIGN

Structurally the *Endeavour* Class vessels were designed and built for a 30-year fatigue life. The vessels are built primarily with mild steel, with little or no reduction in scantlings. Where high tensile steel is used (upper deck in way of the cargo block, sheer strakes, and highly stress details) margins above regulatory allowable minimums are applied. Critical structural areas were studied by finite element analysis, dynamic load approach and spectral fatigue analysis.

Criteria

Based on Polar's Alaskan operating experiences a number of design criteria were established for the structure. First, it was determined that mild steel (primarily ABS Grade A, with some B and D) would be used for structure. If high tensile steel were to be used, a reduction in scantling was allowed, providing there was a minimum 10 percent allowance above the ABS requirements, including corrosion allowance. Structural steel in cargo and ballast tanks was to be a minimum of 12 mm in thickness and was to be no more than 25 mm. For the upper deck, because the double hull construction results in mild steel plate thickness well above 25 mm, the deck is constructed of ABS Grade DH plate. However, by using Grade DH plate, ABS rules allow for a plate thickness of 19.5 mm, including corrosion allowance, but 22 mm plate was used. Sheer and deck stringer strakes are Grade EH plate.

Structural design was developed based on careful engineering. Polar Tankers required that the ships be designed for a 30-year life. Compliance required not only compliance with ABS' SafeHull A and B programs, adjusted to 30 years, but finite element analysis (FEA), structural fatigue analysis and compliance with ABS' Dynamic Load Approach (DLA). Structural details were studied for areas known to experience structural fatigue cracking, based both on ABS and classification society publications, and for areas found to be prone to cracking based on Polar's experiences. During seakeeping model testing, models were instrumented to aid designers in correlating the motions model to actual measurements. Structure was modified based on results of these analyses.

Engineering

Structural engineering for the *Endeavour* Class vessels was a cooperative effort. John J. McMullen Associates led the design efforts in producing the midship section shown in Figure 29. Avondale (Northrop Grumman Ship Systems - Avondale Operations) assisted in the development of the midship section and was responsible for the scantling plans. Avondale was also responsible for running ABS SafeHull Phase A and B. MCA Engineers was responsible for the Finite Element Analysis, Dynamic Load Approach, and the Spectral Fatigue Analysis. A detailed description of the vessels structural design is found in **Millennium Class Tanker Structural Design – From Owner Experience to Shipyard Launching Ways** by James Read, et al. [30].

	Port side	Starboard side
Propeller	Operable	Operable
Rudder	Operable	Locked at 0°

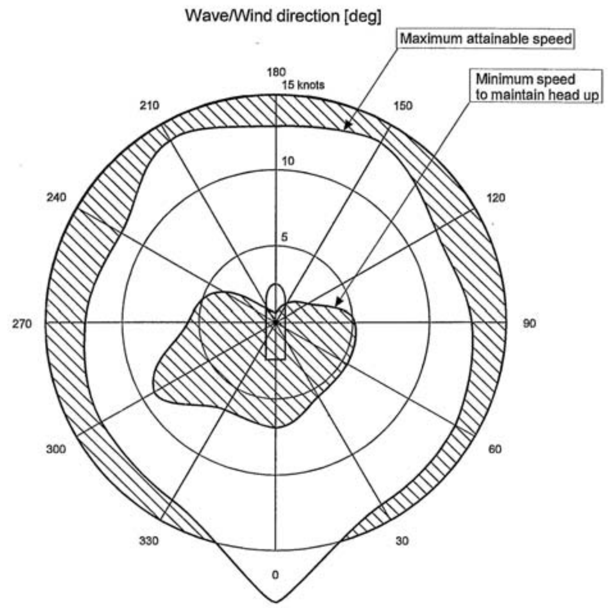


Fig. 25 Operability curves for single rudder failure - Full Load condition

	Port side	Starboard side
Propeller	Operable	Operable
Rudder	Operable	Locked at 0°

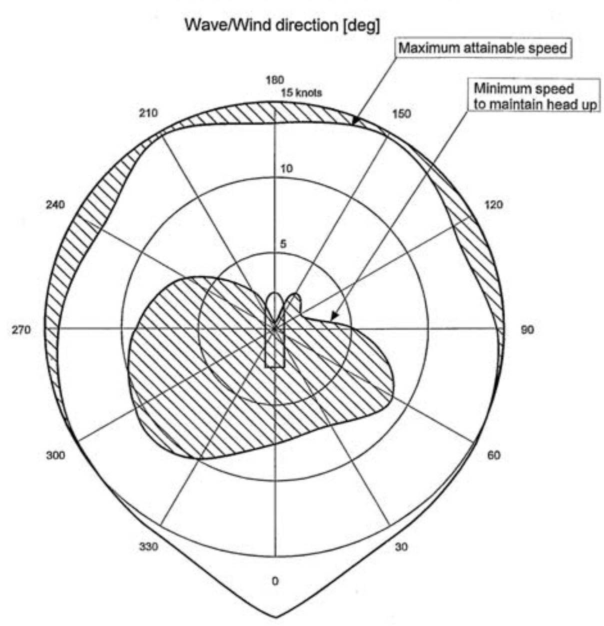


Fig. 26 Operability curve for single rudder failure - Ballast condition

	Port side	Starboard side
Propeller	Operable	Free-wheeling at zero pitch
Rudder	Operable	Locked at hard Stbd (45°)

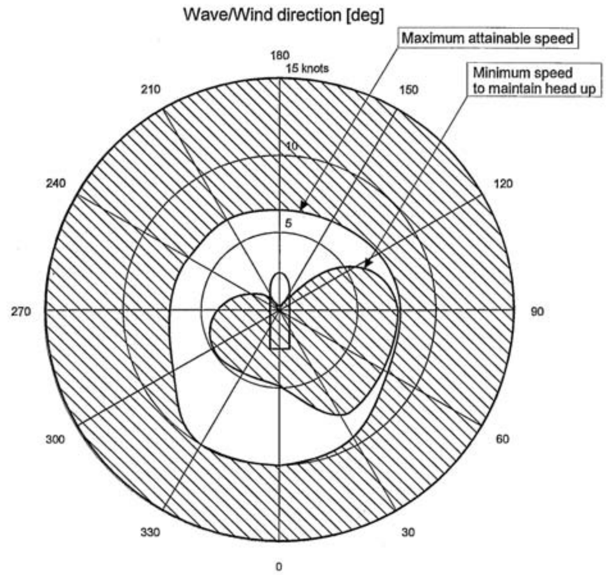


Fig. 27 Operability curves for rudder and propeller failure - Full Load condition

	Port side	Starboard side
Propeller	Operable	Free-wheeling at zero pitch
Rudder	Operable	Locked at hard Stbd (45°)

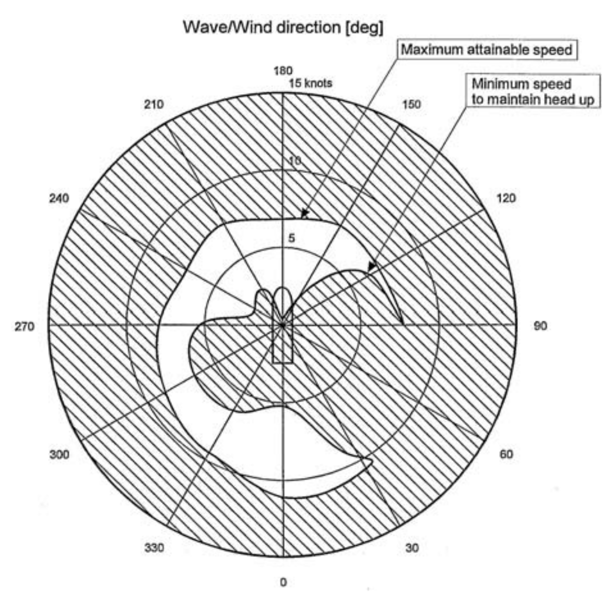


Fig. 28 Operability curves for rudder and propeller failure, Ballast condition

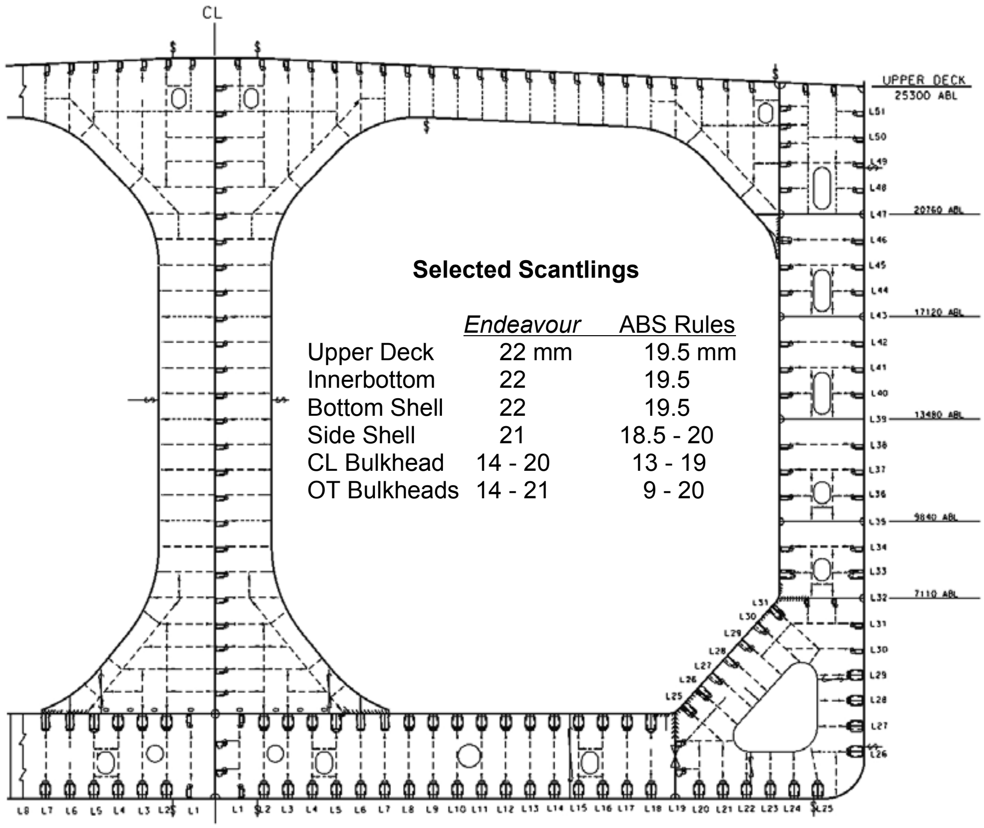


Fig. 29 Midship Section and selected scantlings compared to ABS Rule requirements

ABS SafeHull A & B

The *Endeavour* Class vessels comply with the requirements for ABS' SafeHull Phase A and B certification. As naval architects it is still our position that SafeHull is a good program for checking compliance with the Rules, but it should not be relied on as the primary design tool.

Prior to involving JJMA in the design process Polar found that the naval architects we were working with were using SafeHull A as their primary design tool. SafeHull provided a very efficient tool for making multiple runs to find minimum scantling sizes, which would satisfy Rule requirements. Unfortunately, minimum scantling size and a 30-year fatigue life are not necessarily compatible.

Using conventional methods for designing the midship section and SafeHull Phase A and B a suitable midship section was developed. Through the FEA, DLA and Spectral Fatigue Process some errors were found and changes had to be made. However, in general SafeHull Phase A and B provided an adequate resource for checking Rule compliance during the design process. Some additional structural modifications were found necessary as a result of running SafeHull. Some plate scantlings required increasing and some panel breakers were required.

Finite Element Analysis

MCA Engineers was originally tasked to create one Global, three General Local and nine Detail finite element models for the *Endeavour* Class vessels. The details originally selected were done so based on historical experience operating vessels in the Alaskan trade and information published by the Tankers Structures Cooperative Forum [31].

MCA and JJMA used the information generated in the FEA work to refine the development of the midship section. As the work continued, further FEA studies were done both because of questions generated in the DLA and Spectral Fatigue portions of the structural design and also because of the need to support shipyard production. Because of difficulties in producing mushroom cuts, Figure 30, the shipyard requested we investigate allowable tolerances. The availability of the

FEA let us study the problem and find a workable solution.

Dynamic Load Approach

The Dynamic Load Approach was a new structural analysis tool when it came to designing the *Endeavour* Class tankers. MCA, JJMA, Avondale and Polar had never used DLA and we were unsure as to application or value. Before running the DLA analysis MCA had to first verify wave induced pressure profiles. MCA had historical operating data and projections for our vessels, plus the model test data from SSPA, which they used to verify their computer generated *SPLASH*® model. Using *SPLASH*® and *SCORES-II*®, a strip theory ship motions program, dominant wave patterns and equivalent loads can be calculated. In turn various finite element analyses are performed to analyze particular details.

Ultimately the DLA analysis resulted in increasing the centerline bulkhead thickness at several locations, increasing the depth and thickness of the forepeak frames and one forepeak stringer, increasing the thickness of the lower transverse bulkhead stringers at the connection of the toes to the longitudinal wing bulkhead, adding two brackets between the vertical bulkhead stiffeners and the sloped hopper plating, and modifying the vertical bulkhead stiffeners above the top stringer.

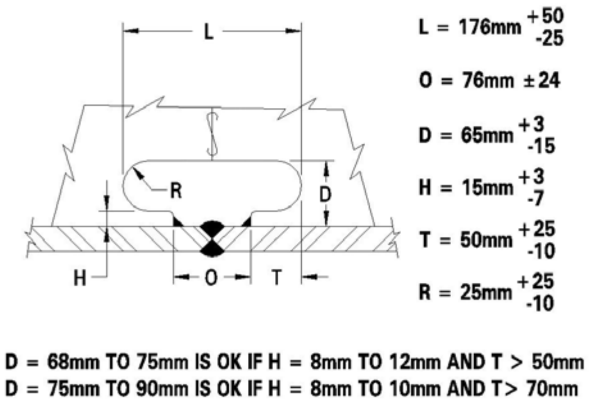


Fig. 30 Construction tolerance for "mushroom" cutouts

Spectral Fatigue Analysis

The fatigue analysis did not produce any surprising results. As would be expected, most of the changes generated in the fatigue studies were of minor significance and involved softening of bracket terminations, changing the shapes of cutouts, modifying the location of erection joint cutouts, changing plate thickness and using full collars at a number of locations. More extensive modifications were required in the hopper area (i.e., the triangular area where the double bottom meets the double side) where some structural modification was required to improve fatigue life. Even after this was done, peening was used on welds to ensure the desired life was achieved. A significant stress riser was found in the connection of the deck longitudinals to the vertical bulkhead stiffeners. Modifications were made to this design to achieve the desired fatigue life.

Structural Design Conclusion

Through the first two years of operations we have not seen any structural cracking in the cargo block of the *Endeavour* Class vessels. This is not unusual in that the cyclical loadings should be nowhere near the point of reaching a crack. However, there is a difference between not seeing any and finding a few. We believe that the *Endeavour* Class vessels have been as carefully designed from a structural point of view as was possible. I do not believe if we were to approach the design again we would alter the approach that was taken. I am confident that the design is the best that we could achieve given the tools that were available at the time the vessels were designed.

MACHINERY & ELECTRICAL

The *Endeavour* Class tanker machinery and electrical systems are designed to fully comply with the latest redundant propulsion requirements. The vessels have two fully independent engine rooms separated by a watertight bulkhead that extends from the keel to the top of the stack. Normal operating practice is to run with a split plant, although cross connection of switchboards and service systems are possible. While both plants are routinely controlled from the starboard machinery control room, full redundancy within the control system ensures a single control failure does not result in the loss of both plants. In case of a catastrophic failure in the starboard machinery control room, the port engine room can be operated from the port machinery control room.

Criteria

The vessels have been certified with ABS as +A1E, Oil Carrier, +AMS, +ACCU, SH, DLA, R2-S+, UWILD, +APS, NIBS. ABS' *Guide for Propulsion Redundancy* was first published in June 1997 and the *Endeavour* Class tankers were contracted for on July 1, 1997 [27]. Because the ABS Guide was new and the *Polar Endeavour* was the first application there were some growing pains with regards to rule interpretations. Most of these issues were minor however, and were resolved easily without serious consequence. To our knowledge, the *Endeavour* Class tankers are the first vessels certified by ABS with a Classification Notation for redundancy.

Design

At the time the *Endeavour* Class design and specifications were being developed only Det Norske Veritas' (DNV) redundant propulsion guidelines were available. Consequently, DNV's RPS (Redundant Propulsion and Separate) guidelines were used as a design standard [32]. As the design developed and ABS' Guide for Propulsion Redundancy became available, ABS' guidelines were used. When there was a difference in the two, the more stringent was used.

Operation

The *Endeavour* Class vessels are designed for operation in one of three default modes, e.g., In Port (Hotel), Cargo or Sea. These modes represent prescribed design alignments of the power management system, as determined during the design stage. The power management system controls one 8.6MW/6.6KV PTO generator, one 6.6KV/480V transformer, one 1000 KW/480V power converter unit (PCU), and one 1000KW diesel generator in each engine room. The power management system also has control of the emergency generator, and the high voltage (6.6KV) and the low voltage (480V and 120V) switchboards.

While the engineers can choose alternative arrangements in case of an upset condition or for maintenance, the power management system will align the plant in accordance with the default settings. Should the designated alignment not be achieved, the power management system will seek alternative arrangements until it is able to stabilize the plant. Initially, this alignment represented a 'best' guess of how the plant was to be operated. Consideration was given to the fact we were making a shift from single screw steam plants to a twin-screw, redundant, diesel plant with PTO generators and a Power Management System (PMS) that could make decisions and take actions faster than any combination of crewmembers we had on any of our tankers. In service, with a small amount of tweaking, the PMS system has proven to be an incredible asset and a key component to the success of the ships.

In Port

The In Port mode, Figure 31, is essentially the hotel condition, where the vessel has only those loads necessary to maintain the accommodations [33]. In this mode, one of the two diesel generators will typically be placed on line, powering both engine rooms, and the second will be placed in standby. The In Port mode may also be used for loading and discharging segregated ballast by powering the high voltage switchboard from the low voltage (LV) switchboard through the transformer. Alternately, all electric power may be taken from one of the main engine PTOs. In service it has been found more often than not that the hotel load exceeds 1000 kW and that both diesel generators must be placed on line.

Cargo

The Cargo mode, Figure 32, is used for discharging cargo [33]. In this mode one of the main engines and its PTO generator is selected to power all hotel load needs and the cargo pumps in a non-split plant configuration. The bus-tie breakers connect the two HV switchboards and the LV switchboards remain split. Ship service power is provided by the PCUs. While pumping cargo, the working engine's clutch is disengaged and the shaft brake is engaged preventing the propeller from turning. The second engine is secured with the clutch engaged.

Sea

The Sea mode, Figure 33, includes operations for both maneuvering and free running conditions [33]. In normal maneuvering mode, the ships will be operated in a split plant configuration, with both PTO generators and both PCU generators on line. For maneuvering, the plant will be operated at 106-rpm (50HZ). From about 12-15 knots, the plant will be operated on a combinator curve where both pitch and rpm will be varied to provide maximum propeller efficiency. Above 15 knots, the vessels will be operated at 127-rpm (60HZ). This provides for constant frequency allowing the PCU generators to be secured and the transformers to be placed on line, conditions permitting. The plants will be kept split under normal at sea conditions. Depending on maintenance needs, both engine rooms can be powered off a single PTO generator.

Split Plant Operation

The value of the split plant operation has been proven to us when the vessel was operating both with and without the plants split. In one case while operating with the plants split on the maiden voyage, a fuel hose to the main engine failed causing a black out of the starboard engine room. The ship's crew worked feverishly to restore essentials before tackling the failed fuel hose problem. In the mean time, the ship slowed to a comfortable 12.5 knots on the remaining shaft. After repairing the failed hose and returning to the control room one of the engineers crossed over to the port control room where an ABB technician had been working through the entire ordeal, oblivious to the failure on the other side!

In the second case the ship was being operated without the plants split. Through a combination of adding loads (i.e., IG blower, engine room ballast pump, fire pump, and deck machinery) while shifting docks, the PCU generators became overloaded. Before the diesel generators came on line the plant blacked out. Power was restored in less than a minute, but the lesson was clear, vessel transits at sea and between docks need to be done with a split plant.

Even with the lesson of split plant operation learned, the Power Management System is being revised. The revision will prevent adding loads that would overload the system because of intermittent startup currents and will refine the load shedding configuration to assure non-essential equipment is taken off line rather than risk tripping the plant.

Transition Modes

A transition period exists each time the operating mode is changed. To get underway (i.e., transition from Cargo mode to Sea mode), the second engine is started and all ship service power is transferred to its associated PCU generator. The first engine's shaft brake is released and the engine is slowed, allowing the clutch to be engaged (at 35 to 50 rpm), after which the engine is returned to maneuvering speed (106 rpm), and the PTO generator is placed back on line. The two plants are then split ensuring a single failure will not result in a total loss of propulsion or steering.

Machinery Design

The machinery plant for the *Endeavour* Class vessels reflects an evolution in the design of the plants that were in common use on the North Sea shuttle tankers. Much of the design is a result of the creative engineering of the marine engineers at IZAR, Renk and VULKAN, along with our ability to approach their ideas with an open mind. None of the proposed changes would have been possible had it not been for the reality checks that the engineers at JJMA provided, ensuring that we were progressing on a sound engineering basis.

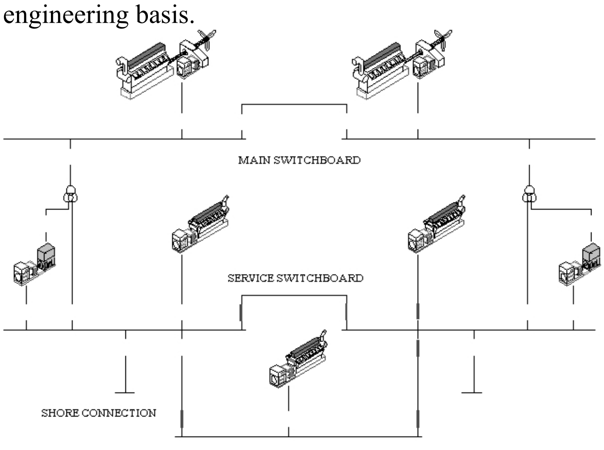


Fig. 31 Plant configuration - In Port (Hotel)

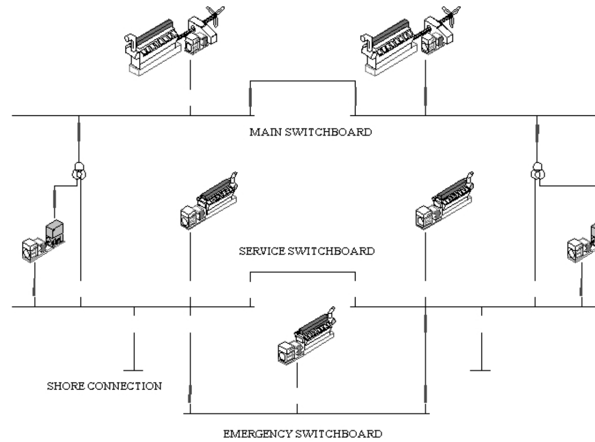


Fig. 32 Plant configuration - Cargo

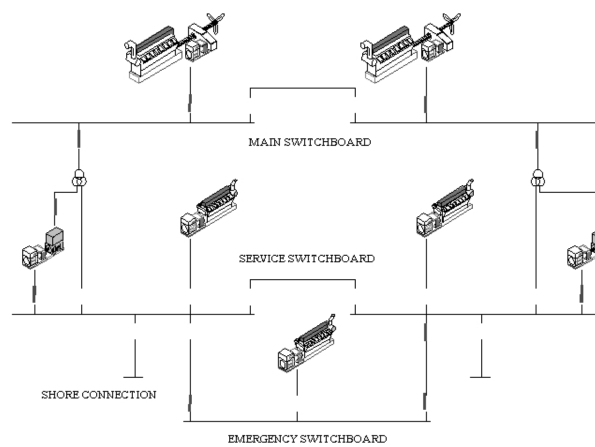


Fig. 33 Plant configuration - Sea Mode

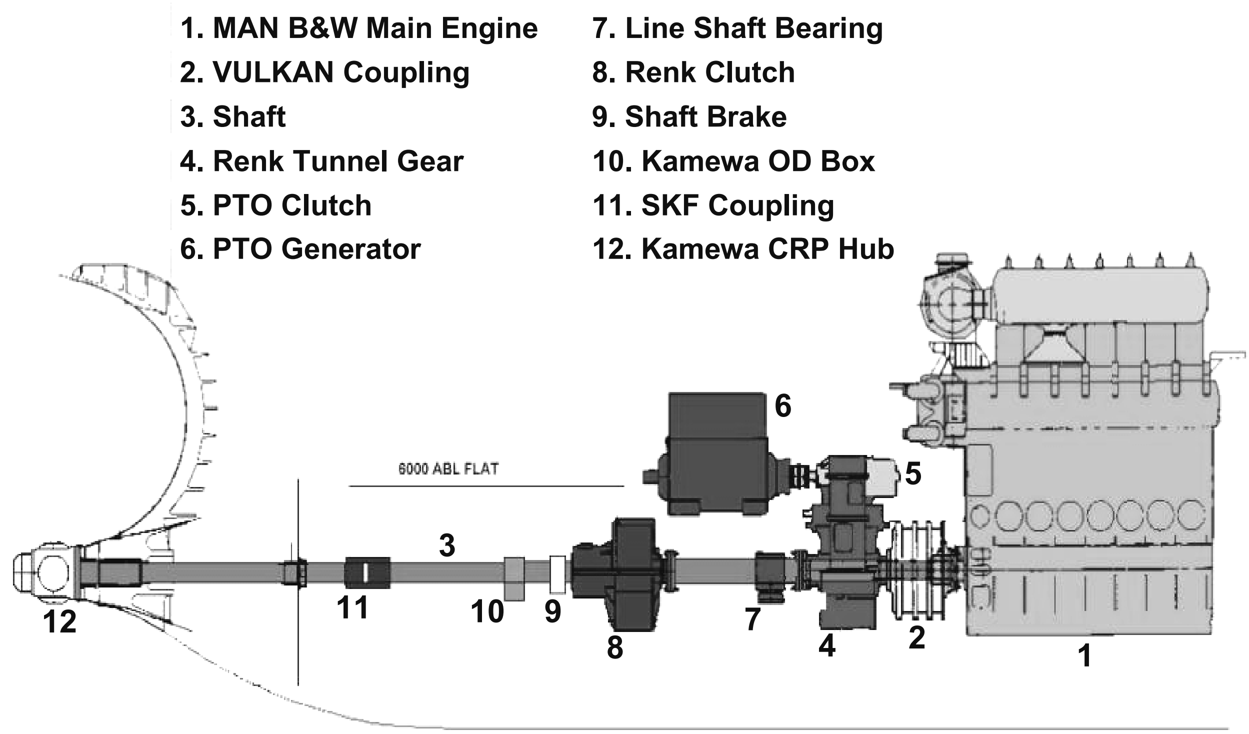


Fig. 34 Drive train components

Drive Train

The drive train, Figure 34, on initial inspection, appears typical of slow speed diesel, PTO generator and CP wheel installations. However, closer examination yields a unique solution utilizing a tunnel gear (Renk), flexible rubber coupling (VULKAN) and a hydraulic friction clutch/thrust bearing combination (Renk) designed with fully redundant hydraulics. Although representing a number of innovations, the drive train was developed based on the proven technologies of a number of leading manufacturers.

Engines

The *Endeavour* Class tankers are supplied with two MAN-B&W 7S50MC-C slow speed diesels rated at 11,060 kW (15,015 BHP) at 127-rpm. The engines are rated for a specific fuel consumption of 171 g/kWh (126 g/BHPh) when burning fuel with a lower calorific value of 42,700 kJ/kg (10,200 kcal/kg) at ISO conditions. In simpler terms, the vessels are expected to burn 500 bbls/day of 700 cSt fuel with the engines at 90% MCR and the PTO generators providing ship service power. This equates to 16.5 knots loaded (125,000 DWT) and 17.3 in ballast at a delivered power of 18,156 kW (24,347 BHP). In comparison, our 120,000 DWT steam vessels burned about 850 bbls/day at 15.5 knots loaded and 16.2 knots in ballast at 17,600 KW (23,600 SHP).

Polar, in their desire to build an environmentally friendly vessel, elected to upgrade the engines on the *Endeavour* Class tankers to make them MARPOL Annex VI compliant. This decision was made in the summer of 1999 and testing occurred in the fall of 1999. At the time MAN-B&W predicted a loss in fuel economy of about 3%. Test bed results showed that at 11,060 kW (15,015 BHP) at 127-rpm the engines had a specific fuel consumption of 178 g/kWh (131g/BHPh). At lower powers this difference would be more pronounced. Still after entering service with the Annex VI Low NOx configuration the average daily consumption was still only 520 bbls/day.

In October 2002 MAN-B&W and IZAR approached us with a belief that they could improve fuel economy. They felt that in the original testing they had sought “a solution” rather than the “optimum solution”. In a series of tests where fuel valves, turbocharger diffusers, and turbocharger nozzles were varied an optimum solution was sought to find a compliant engine. After completion of the modifications and retesting, the engines showed consumption of 170 g/kWh (125.3 g/BHPh). Overall, with minor modifications to the turbochargers, i.e., changing the inlet nozzles and changing the fuel valves to conventional valves, it is possible to comply with Annex VI and to achieve better fuel economies.

During the first year of service the engines have suffered from an undue amount of cylinder head erosion in way of the nozzles. At first this was blamed on the low NOx nozzles. However, MAN-B&W quickly discounted the possibility that the nozzle design had anything to do with the erosion. Erosion rates were such that the first cylinder heads showed a loss of 3 to 4 mm of material in the first 60 days of full operation between the shipyard and the West Coast of the United States. Working with MAN-B&W and Goltens, Polar began removing the cylinder heads on a rotational basis to have them clad with Inconel® in way of the areas of erosion. By the time this process was complete on the first engine the depth of erosion on the last heads had reached 10 mm. On future engines, the cladding will be done long before erosion depths reach 10 mm. In fact, the last two engines were clad before leaving the factory.

It is believed that the erosion is a result of operating the engine with a controllable pitch propeller and with the PTO on the generator curve, rather than the propeller curve. MAN-B&W, based on previous experience, believes that as load is reduced there is some fuel, which is not burned and it forms carbon deposits on the cylinder heads near the nozzles. These carbon deposits later burn at higher temperatures resulting in the erosion. The Inconel® cladding offers a workable solution for both Polar as an operator and MAN-B&W as the engine designer. The cladding appears to have fully solved the problem.

Tunnel Gear

The Renk type BSL 225 tunnel gear provides power to the PTO generator directly from the main engine by way of the VULKAN coupling. The drive for the propeller shaft connects directly to the main engine and passes through the tunnel gear, without making physical contact. The tunnel gear steps the input speed from 127-rpm to a 1200-rpm output speed to the generator. It is fitted with a multi-disk clutch that allows the generator to be connected or disconnected, as well as with three gear-driven oil pumps. The pumps provide hydraulic power for the clutch after the gear has been brought up to speed, and for lubrication of the gear.

The tunnel gear also offers another capability we hope never to use. In the event the generator, VULKAN coupling or gear become disabled, the VULKAN coupling can be removed so the gearbox and generator are essentially removed from the drive train. This enables the ship to continue operation on both shafts, at full power. Similar failures on ships without tunnel gears could render the shafts inoperative.

VULKAN Coupling

The VULKAN RATO S 7330 coupling provides the connection between the tunnel gear and the main engine. It consists of 18 rubber wedges, each weighing 500 kg, that provide for misalignment and vibration isolation. Because of the unique design of the VULKAN couplings, requirements for torsional vibrations could be met without adverse effects on design or cost.

After sea trials on the *Polar Endeavour* there was some question as to the performance of the VULKAN coupling and it's predicted dampening with regard to torsional vibrations. After much discussion it was decided to change one of the rows of the coupling from rubber to silicone rubber. The silicone provided greater flexibility and would not stiffen as it heated. The new silicone couplings were placed on the second ship for trials. It was at this time that it was discovered that an internal bushing used to assemble the coupling was binding and that it was having an affect on the coupling performance. After trials the coupling was disassembled the bushing was bored, lubricated and reassembled. Now with the silicone rubber elements in place, because of their additional flexibility, in certain conditions generator instabilities are encountered. We believe the ultimate solution to the instabilities lies in the clutch in/clutch out speed, which is easily changed through software modification. We are currently working with IZAR, Norcontrol, VULKAN, and JJMA to define the problem and to find a permanent solution.

Clutch/Thrust Bearing

The VULKAN coupling and tunnel gear options were presented early in the detail design process. They were accepted as viable alternatives to mechanical couplings and conventional gears, after careful study, soon after detail design started. Acceptance of the hydraulic disk clutch was not as quick. All of the clutches we examined were conventional gear clutches that were manually operated. Clutching/de-clutching with gear clutches requires a crewman to go to the clutch, open the cover and jack the clutch in or out, making sure required alignments are maintained. Although inconvenient, the mechanical clutching arrangement was found acceptable, although access was limited.

The gear clutch was ultimately found to be unacceptable due to concerns of inherent hammering of the clutch resulting from axial vibrations, generator harmonics, and unbalances in the main engine (i.e., misfiring). To deal with these problems, Renk proposed a combination thrust bearing and friction clutch, type TB/FC 500, Figure 35 that had no gears that could hammer. The clutch could also be engaged/disengaged remotely. To satisfy our redundancy requirements, Renk designed the clutch with two independent hydraulic circuits, each capable of transmitting 100% of the rated torque. Under normal operations both circuits are engaged, however the ship could operate on a single circuit.

In service the Renk clutch has performed admirably. If there is a complaint, it is that we did not have foresight in locating the support equipment needed for the hydraulic systems. While the pumps and filters must be located in the bilge area to assure suction, the control equipment does not. The controls would have been more serviceable had they been placed a deck above the bilge where there was better access.

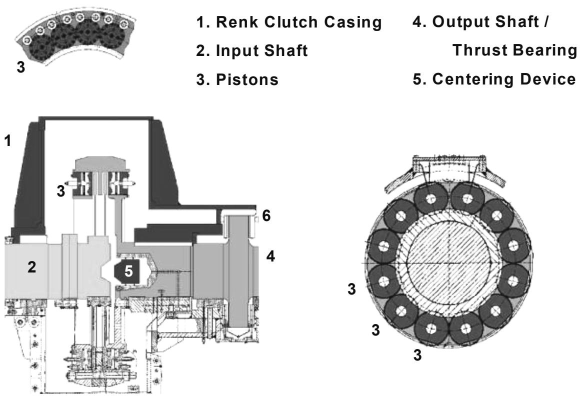


Fig. 35 RENK hydraulic clutch, Mechanical arrangement

Propeller

The ships are fitted with two Kamewa controllable pitch propellers. The propellers are four bladed, 5.8m diameter, Nickel Aluminum Bronze, with a 33^{o} skew. The propellers are designed with a 30-year fatigue life for the blades, hub and internals and are finished in accordance with ISO R484 Class I requirements. To ensure performance of the Kamewa designed propellers, all self-propulsion and cavitation model testing was re-done using the final propeller design.

Polar did consider acquiring one set of stainless steel blades polished to an ISO R484 Class S finish. This change was never brought to fruition. Should these propellers suffer from unusual cavitation wear, the stainless steel blades would be one way to improve efficiency and prevent wear simultaneously. At this time the propellers on the Endeavour have been examined three times by divers, at six, 12 and 18 months. The propellers show no cavitation or other damage. In fact, the propellers have surprisingly retained their original level of polish. While stainless steel blades will always be a possibility, based on current knowledge, they will most likely never be needed.

Steering

Steering is accomplished through Porsgrunn "IMO" type rotary vane steering gears. The Porsgrunn units meet or exceed all IMO standards for tanker steering gears. Although the steering gears are of the "IMO" configuration, they are installed in compliance with the USCG Code of Federal Regulations (CFR). The primary difference between the two is that IMO allows the two steering gear pumps to operate simultaneously providing higher operating speeds. Whereas, the CFRs require that the two pumps be operated independently. From an operator's standpoint we could find arguments for both, but strong preferences for neither.

The steering gears are capable of operating from 35^{o} to 35^{o} at vessel speeds greater than 12 knots, and 45^{o} to 45^{o} at speeds below 12 knots. The Raytheon Integrated Bridge controls switch from 35^{o} to 45^{o} electronically.

To date the greatest issues encountered with the steering system have been due to a lack of experience. Historically, all of Polar's vessels were single screw fitted with ram steering engines. Twin screw, rotary vane systems offer new challenges and experiences. We have discovered differences in response rates between the rotary vane and the ram systems and cycling due to the inherent leakage of the vanes. This in turn has led to the premature failure of some amplifiers. We have also found some anomalies in where the "correct" position of the rudders should be when at sea. One vessel tends to have its rudders stay in one position while another has them skew to a different position. There is some thought that this makes the steering gears work harder, but in checking with other operators the amount they work is consistent with their experience. We are investigating installing "staged" pumps rather than the single screw pumps provided. We believe this will cushion the slamming of the rudder experienced when small corrections are needed. Our ram type steering gear are generally fitted with three pumps. Depending on the degree of change required, one, two and three pumps come on line in series. We have talked with one company that has considerable experience with this type of retrofit on rotary vanes and they have indicated we would be pleased with the change.

Electrical

Development of the electric system represents the one area where there was a great amount of design change. Based on Avondale's recommendations the system evolved from earlier designs to the twin PTO generators, twin transformers, twin PCU generators (historically Power Converter Units have been called motor generator sets in the United States) and twin diesels now installed. The development of the design centered on providing maximum operability along with maximum redundancy for a vessel built with two completely separate engine rooms. Design was dictated not only by compliance with the R2-S+ requirements, but with providing a plant that was truly operable.

A sole source vendor in accordance with the Ship's Specifications is providing the electric system. ABB will provide all motors, controllers, switchboards, generators and automatic controls for the electric system.

Arrangement

Figure 36 shows the one-line diagram for the electric system. As can be seen each engine room's design is equivalent to a single screw power plant. A PTO generator and transformer/PCU generator combination provide one source of electric power, while the diesel generator set provides the second. Bus-tie breakers, providing both redundancy and flexibility in operation, interconnect each engine room's switchboard.

PTO Generators

The Power Take Off (PTO) generators are 8.6MW/6.6kV, 1200-rpm machines operating off the PTO gearbox. The PTO generators are designed to generate power between 50 and 60Hz. They may be clutched in at main engine speeds up to 80-rpm or de-clutched at any speed. They are designed to operate in parallel with each other for closed transition power transfers only.

PCU Generators

The PCU generators are powered from an AC/DC inverter that receives 690V input and provides a 660V DC output. The DC output is used to power a DC motor, which in turn drives a 1000 kW, 480V AC generator. The AC generator is identical to the diesel generators. The PCU generators are designed to deliver constant 60Hz ship service power at any PTO generator output frequency between 50 and 60Hz.

Diesel Generators

The diesel generators are conventional sets powered by Bergen 6-cylinder diesels. The diesels are capable of running on heavy fuel but have been provided with MDO as the fuel source. The diesel generators are intended for use in the In Port mode and during some transitional periods. They are mainly intended as backups to the PCU generators.

Transformers

The 6.6KV/480V transformers are proving to be far more useful than first expected, particularly when weather conditions permit their use. The transformers eliminate the use of the inverters on the PCU generators and the DC motors, saving approximately 500 kW per shaft in energy. Because the transformers are used at periods where there is little variation of propeller pitch and governor movement, fuel rate tends to be steadier, giving better overall fuel economies. Also, the transformers are virtually maintenance free in comparison to the PCU generators.

To date, we have found that normal variation of frequency has the greatest effect on the purifiers. None of the other equipment has demonstrated problems associated with minor frequency variations. Because of the behavior of the purifiers, the transformers are secured and the PCU generators are placed on line. We are currently experimenting with variable speed motor controllers for the purifiers in hopes we can isolate them from changes in frequency. This will enable us to keep the transformer on line for longer periods of time.

Switchboards

The *Endeavour* Class vessels electrical systems have both high and low voltage switchboards to support the high load requirements (i.e., cargo pumps and bow thruster) and the normal daily ship's loads (i.e., 480V and 120V)

High Voltage (HV)

The vessels are fitted with two high voltage (HV) switchboards, one in each machinery control room. The HV switchboards are designed to operate at 6.6KV from 50 to 60Hz. The starboard HV switchboard services two cargo pumps, the cargo stripping pump and a segregated ballast pump. The port HV switchboard services two cargo pumps, the crude oil washing pump, a segregated ballast pump and the bow thruster. The port HV switchboard is also fitted for the future installation of an 8.6MW shore power breaker, which will allow for powering the vessel from a shore power source for cargo discharge. Each HV switchboard connects to a step down transformer, which can power a PCU generator or the 480V switchboards directly. Two bus-tie breakers interconnect the two HV switchboards, one in each machinery control room.

Low Voltage (LV)

The vessels are fitted with two low voltage (LV) switchboards, one in each machinery control room. The LV switchboards are designed to operate at 480V/60Hz constant frequency. Each switchboard can be powered from a 6.6kV/480V transformer, a 1000kW PCU generator or a 1000kW diesel generator set. Each switchboard powers a 120V, 60Hz service switchboard. Two bus-tie breakers interconnect the two LV switchboards, one in each machinery control room. The two 120V switchboards are not interconnected and must be powered from their respective switchboards. A unique feature of the LV switchboards is their division into two sides with one vital service feed (i.e., fuel pump) on each side of the switchboard. Each side of the switchboards may be isolated from the other by a disconnect breaker. This feature allows maintenance of the switchboard without securing the plant. A 1000kW shore power connection is provided for each switchboard.

Power Management System

The key to the electrical system is the Power Management System (PMS). To operate and control the electric system ABB, in conjunction with Avondale Shipyard and Polar, developed a system specifically for the *Endeavour* Class tankers. The PMS incorporates such features as load shedding and sequential restart, along with full control of the electrical system. The operators can choose any allowable configuration of generators and switchboards, and can designate standby scenarios. The PMS, on sensing upset conditions, will determine the proper course of action to maintain the plant in its current operating condition. This course of action could be closing bus-tie breakers or bringing standby generators on line. In each case, available power will be sensed and the time needed to bring the plant back will be determined and the fastest choice will be taken. The PMS can start and stop generators, parallel generators, open or close tiebreakers, and shed load or restart essentials, as required to keep the plant on line.

The PMS always starts from default conditions that have been determined in advance. However, the ship's crew has the ability to alter configuration according to the conditions that they are currently working. The value of the PMS to date has been its flexibility. As we've gained knowledge on the operation of the vessels, added equipment, learned about impacts of load shedding and sequential restart, we've been able to address these issues without redesigning the system, or replacing it.

The other value has been the acceptance and trust the operators have shown in the equipment. To date problems encountered have mainly been associated with loose connections. In some cases we are improving the strength of housings, in other cases it will require periodic inspection and tightening of fittings by ship's personnel.

Automation

The automatic controls for the *Endeavour* Class vessels will play a major role in their success in service. Besides certification for +AMS and ACCU by ABS, the ability to operate the plant as designed is fully dependent on the design, construction, operability and maintainability of the automation. Prior to deciding on the Specifications for the automation we consulted with the automation experts at what was then our Cherry Point Refinery for input as to state-of-the-art automation used in refineries. We found automation systems should be designed with redundant busses to assure operation in the event of a single failure, should rely on personal computer based technologies using current microprocessors, should have sufficient capacity to handle any conceivable future expansion, should not rely on distributed processors, and should be "backwards compatible". "Backward compatibility" is referring to the ability of the automation system to accept and utilize advancements in technology without becoming obsolete. For instance, current pressure sensors collect signals and send the signals to Input/Output (I/O) processors, which in turn send the signals to the master processor. The next generation of pressure sensors will have the I/O processors built-in.

Automation for the power plant, Figure 37 includes not only the two engine rooms but also covers the power management system (electrical), main engine safety systems, main engine governors, power plant operation, and propeller control [33]. ABB Industri AS of Norway is providing the main automation, power management and cargo control systems, and is integrating the Kamewa CANMAN® controls for the propeller and bow thruster, Saab Tank gauging system and the Norcontrol engine governor and safety systems.

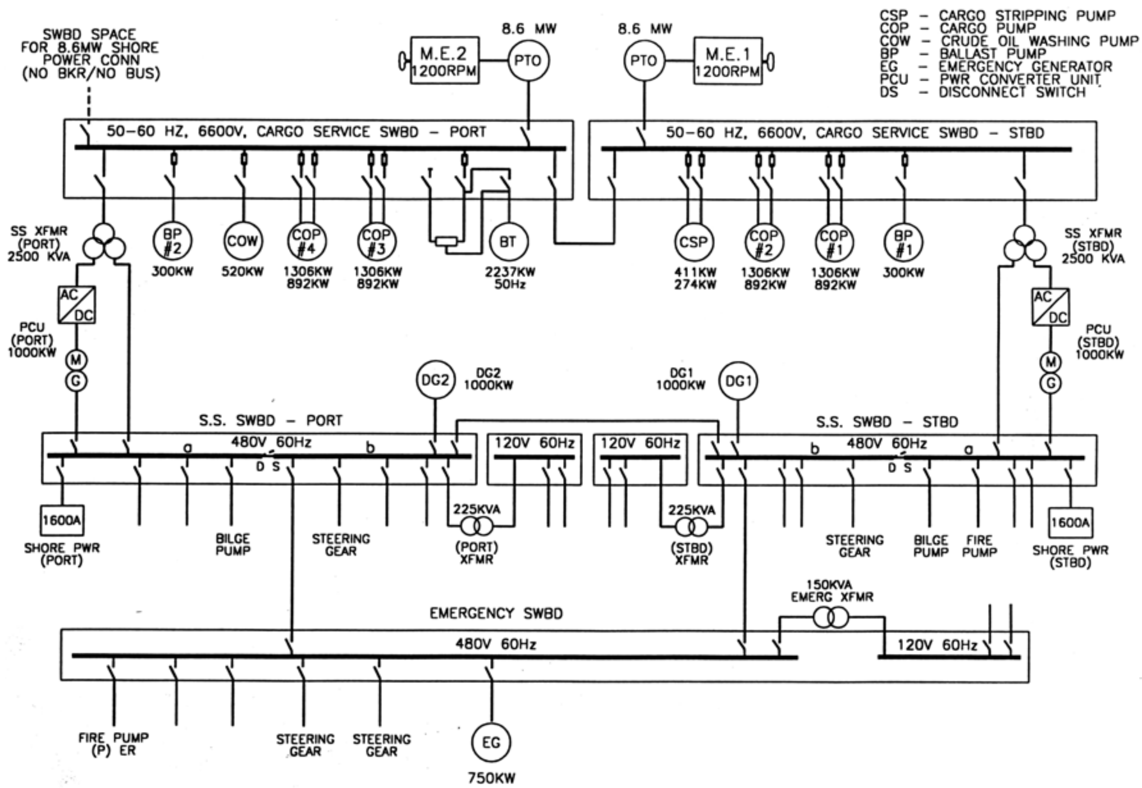


Fig. 36 One-line diagram

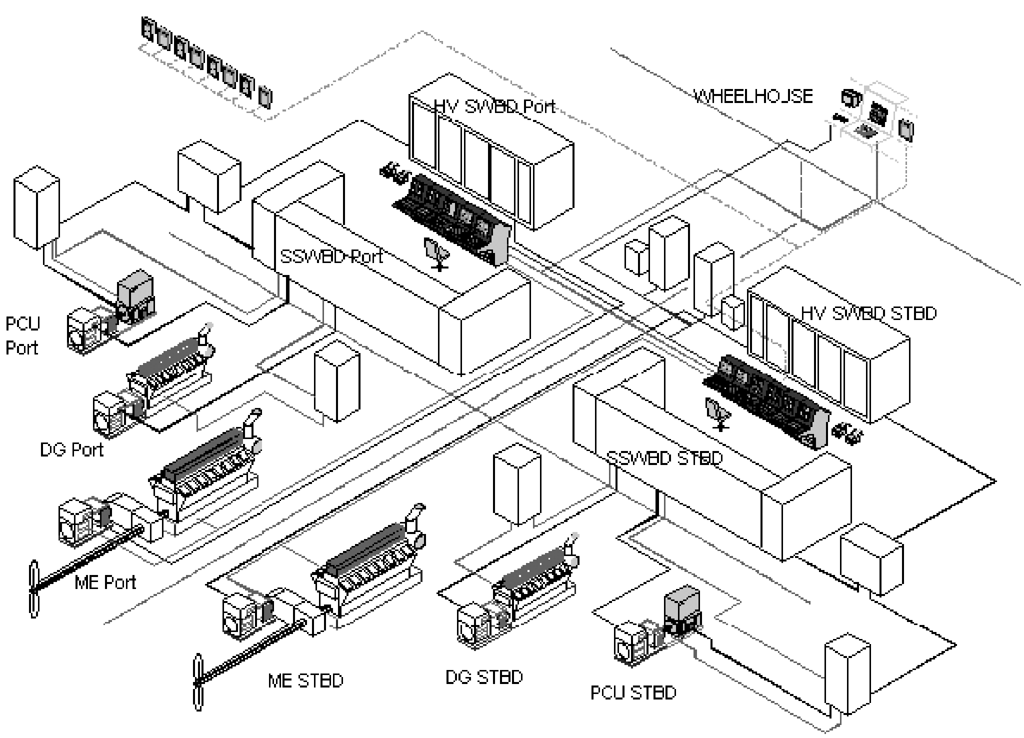


Fig. 37 Automation control system arrangement

ABB

The ABB automation system is based on two redundant PCs (Advant Controller AC450) located in each engine room. These PCs handle all engine room, power management and cargo control requirements. Each PC is capable of controlling about 5,000 input/outputs individually. The *Endeavour* Class tankers have a total of about 4,000 points that are being monitored or controlled. As installed, one PC is capable of operating the vessel, and four are fitted. Two PCs, one in each engine room, are kept on line at all times, with the second set of PCs in standby. The ABB system is based on commercially available Pentium II® processors and a UNIX® operating system. The system utilizes a redundant data bus, and efforts have been made to isolate vital components so that no single failure will result in the loss of the plant. All equipment being used is off-the-shelf ABB supply.

The ABB automation system may be operated from any one of the seven control stations located throughout the ship (two in each machinery control room (MCR), two in the cargo control room, and one on the bridge). Each control station consists of a 21" color monitor and a dedicated keyboard with track ball. Certain functions may be locked out of specific control stations (e.g., starting of main engines from the cargo control room) based on normal operations. However, access to all operating functions at any control station is possible by use of keys and password protections. Control mimics are fully developed. However, as the vessels have entered service and the crew has found need for change we have found it fairly easy to have ABB make modifications, and to have the modifications transferred to the sister vessels. The mimics are a combination of system mimics (i.e., lube oil service, fuel oil service, compressed air, etc.) and function mimics (i.e., starting the main engine, bringing a propeller shaft on line, etc.). The function mimics include all those items needed for the function (e.g., start air, lube oil, fuel oil, etc. for starting the main engine).

Of particular interest in the ABB system has been the ability to upgrade the system as we've found need. In particular is the inclusion of additional alarm and monitoring points that were not present in original scope. We've also added the ability to connect the system directly to Oslo, where a qualified service technician is available 24 hours a day. This technician, upon being called by the Chief, and being connected by the Chief can access the system to analyze problems and to correct them. Software can be changed while the vessel is at sea operating, instead of waiting for it to return to port, when the problem no longer exists. Another upgrade that is expected to be made in the not to distant future is to change from paper alarm, bell and data loggers to electronic loggers, making data recovery quicker, easier and more efficient. Instead of wafting through thousands of points trying to find the first point of failure in the tree, the chief will be able to scroll through the list. ABS and the USCG have given approval to our proposed data logging system. Again, we believe this will be an industry first.

An unexpected benefit of the ABB system has been the increased awareness of the engine room and engine performance that has come with placing an Operator's Station (OS) on the bridge. The Deck Officers no longer call the engine room when getting ready to leave the dock to check when engines will be ready. They now monitor the OS station mimic screens to seen when shafts are clutched in and when the Power Management System is lined up properly. They know in advance if the engine room is having problems because they can see the same monitors and alarms on the bridge. At sea they now monitor propeller speed, power and torque. When sea states are such that the loading of propellers is too high they have ready access to data to use in conjunction with the Hull Monitoring System to change course or to slow. Because of the new data available, at recent Bridge Team Management training courses there has been a greater call for information on the engine room to improve engineering understanding.

Norcontrol

Norcontrol is providing the governor and the engine safety shutdown system for both main engines. A Norcontrol Model 8800E electronic governor is being provided, along with a Norcontrol Model 8810 ship safety system. Both of these systems are furnished as part of the main engine package. Of particular note has been Norcontrol's full cooperation in interfacing its controls with the ABB system.

To date there have been no significant issues with the Norcontrol system. We have experienced some problems with governor instabilities that are associated with the flexibility of the VULKAN couplings. This problem appears at this time to be somewhat inherent in the design, but certainly is neither incurable nor something that we cannot live with.

CARGO SYSTEM

The cargo system on a tanker is the ship's life/blood system. No one ever takes notice of a successful transfer, however, if there is a problem everyone notices. Simple delays or slowness in loading or discharge results in claims and complaints from the terminal. Cargo retained on board (ROB) results in claims and lost tonnage on following voyages. Then there is every tanker owner's and crewmember's nightmare, the error or failure that result in a spill, large, small or miniscule, which must be avoid at all costs.

Polar decided on a number of radical departures from what had been the norm for their cargo transfer systems. First, because of the machinery plant design, conventional steam turbine cargo pumps were to be replaced by electric pumps powered from the PTO generators. Another radical departure was the shift in control of bunker loading and the transfer of engine room ballast from the engineering to the deck department, effectively breaking an 85-year tradition. Reasoning for this change is simple, control. If the deck department was to control hull trim and stress during cargo loading and discharge they needed full control of all operations. The last change, which required the most adjustment, was the elimination of a conventional cargo control console in favor of a modern electronic system featuring two CRT control consoles, a dedicated tank level console and the loading computer, Figure 38.

Fig. 38 Cargo control console

Criteria

The design criterion for the cargo system was simple. The vessels had to be able to load fully in 12 hours, and had to discharge ballast using gravity and pumping in 10 hours. Cargo pumps were, by Specification, to be capable of averaging a discharge rate of 50,000 bbls/hr. over the entire discharge, including stripping and tank washing operations, or to deliver 60,000 bbls/hr when the tanks are half full, whichever resulted in the higher rating, with a rail pressure of 150 psig. Cargo, ballast and fuel loading control are from a cargo control room located on the "A" (second) deck level.

The cargo control system was to consist of a stand-alone package that would be capable of operating all cargo, ballast, and valves associated with the loading of bunkers. Valve control was to be hydraulic for cargo tank valves, deck and pump room valves, and for engine room valves. Tank gauging was to be by radar (SAAB) for cargo tanks and pressure (Autronica) for ballast and service tanks. CargoMax® was to be used for the loading computer.

Initially, it was decided that the cargo watch officer's control was to be limited control of the starting and stopping of the cargo pumps, and in selecting high and low speeds. Specifically, it was decided that the engineering watch officer was to have sole control for the variation of main engine speeds between 106 (50Hz) and 127 (60Hz) rpm.

Design

The cargo systems on the *Endeavour* Class vessels are simple. It is this simplicity that makes them easy to load and discharge. The vessels are fitted with 12 cargo and two slop tanks, arranged two across with a centerline bulkhead. The ballast tanks are arranged into a forepeak, six pairs of "J" tanks in the cargo block, two after ballast, and two after trim tanks. Tank arrangements were shown previously in Figures 2 and 3.

The cargo system consists of two bottom mains, each serving alternate pairs of cargo tanks. Each main splits at the pump room to supply the cargo pumps. The four electric two-speed motor driven cargo pumps deliver 60,000 bbls./hr. when the tanks are half full, with a delivery pressure at the ships rail of 150 psig. The maximum loading rate is 110,000 bbls./hr. The cargo system is designed for loading through a four-header manifold that combines and drops into the two-cargo mains, one port and one starboard. The cargo pumps discharge into two discharge headers that run through the cargo tanks with risers at the cargo manifold, thereby reducing chance of deck spills.

The cargo system is also fitted with a dedicated electric motor-driven crude oil washing pump that powers the crude washing machines. Stripping is accomplished by a dedicated motor-driven positive displacement (rotary) stripping pump, which is connected to a dedicated stripping main. The stripping pump discharges to the cargo pump discharge headers, downstream of the cargo pumps. A stripping eductor, powered by the COW pump, is fitted as a backup to the stripping pump. Schematics of the pump room and tanks are shown in Figures 39 and 40, respectively. Please note that Figures 39 and 40 are mimic displays from the ABB cargo control/automation.

Segregated ballast is loaded into the cargo area double-hull ballast tanks by gravity and by two motor-driven ballast pumps. The segregated ballast mains are run on both sides of the centerline bulkhead, with connections to both the port and starboard headers in each tank. This installation provides redundancy should a ballast pump or tank valve fail. Stripping is accomplished by the use of an eductor powered from the fire pumps.

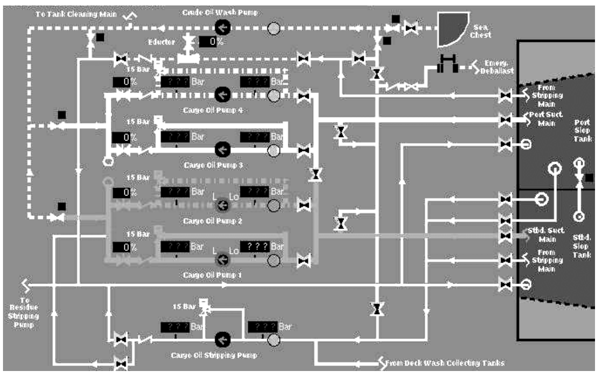


Fig. 39 ABB display mimic of Pump Room cargo piping

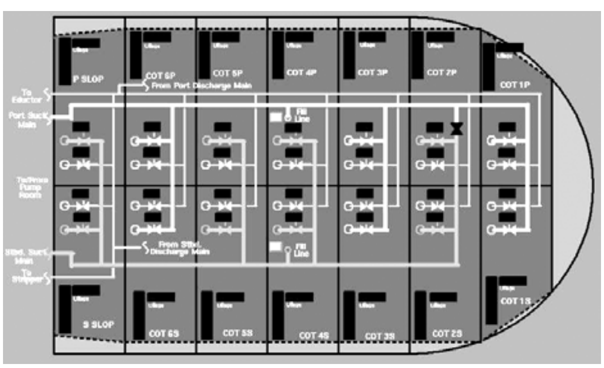


Fig. 40 ABB display mimic of in-tank cargo piping

Unique Features

As the design of the Machinery Control System (MCS) developed, Polar decided it was in their best interest to utilize the MCS for both machinery space automation and cargo control. Despite recommendations from the shipyard for standalone systems, Polar felt that they would have the greatest amount of control from a single system. This decision has proved to be far wiser that ever anticipated. Originally, the *Endeavour* Class vessels were to discharge primarily at two docks where full discharge rates are the norm. However, as a result of corporate mergers and resulting changes in trading patterns, the vessels discharge at a large number of docks and at various rates.

Using a single MCS/Cargo Control System for control of engine speed allowed the flexibility to give the cargo control officer not only the ability to start and stop motors and to vary motor speeds between fast and slow, but also to control engine speed to meet dock needs. For ballast transfer operations the cargo control officer controls all loading and discharge in the engine room, including the starting and stopping of pumps and the opening and closing of valves. All this has enabled the machinery control room to remain unattended during loading and discharges, allowing the engineers to focus on maintenance needs.

Also unique to the *Endeavour* Class vessels is the valve actuation arrangement in the ballast tanks. Polar, finding the placement of hydraulic actuators inside ballast tanks to be somewhat of an anomaly in logic, insisted that ballast tank valves be actuated by reach rod. Unfortunately, because of the lengths and the numbers of bends and elbows needed, it was not practical to use reach rods. Rather, than abandon their concerns and accept normal actuators, Polar designed a system for enclosing the hydraulic actuators (U.S. Patent No. US 6,176,248 B1). This system provides a secondary barrier that catches any leakage from the actuator and its associated fittings. It also provides a means for sensing the presence of hydrocarbons in the void space between the actuator and the secondary barrier. To date there has been one instance of a leaking actuator. The secondary containment would have been completely effective, but it was found that modifications had been made from the patent design and there were problems with installation, which provided a means of escape for a very small amount of oil. This problem is being addressed.

The use of having the cargo pump discharges return to the manifold through the cargo tanks, rather than rise in the pump room and run down the upper deck is catching on in the tanker industry. This simple change reduces the pipes on deck, limits the numbers of flexible expansion joints, and thereby reduces the risk of leaks or spills. The *Endeavour* Class vessels not only took this opportunity, but also eliminated the flexible expansion joints in the crude oil wash (COW) and inert gas (IGS) lines on the upper deck, further reducing the chance of leakage.

One of the easiest tasks to accomplish and one of the most appreciated by the deck officers was raising the Cargo Control Room from its normal position on the upper deck (first) to the “A” (second) deck level. Historically, cargo control rooms had limited visibility, either due to the low numbers of windows or to the various obstructions found on the upper deck. The *Endeavour* Class Cargo Control Rooms are above these obstructions and two 2000 x 800 mm windows provide more than adequate visibility. Add to this a closed circuit TV system that monitors the pump room and the upper deck and watch officers have far better control of transfer operations.

NAVIGATION & BRIDGE EQUIPMENT

The wheelhouse was one of the more interesting design problems. It brought together the traditions of years of seagoing experience on ARCO and Polar's vessels, new state of the art electronics, at the time unseen by anyone but the naval architects, and European insight into how "modern" ship bridges needed to be arranged for better comfort and efficiency.

Wheelhouse

The first argument encountered was one of closed versus open design. Should the bridge wings be fully enclosed? Or, should they be left open, as they had always been? Or, should some compromise position be found. European operators, particularly in the North Sea areas had long gone away from open bridges, finding both improved operator comfort and better performance of electronics. The improved comfort of operators translated to better attentiveness and better awareness during watches. The better performance of electronics translated to reduce maintenance due to exposure to salt air. Arguments for the open bridges were that you couldn't hear as well and that you couldn't sense the wind, particularly during docking situations.

It was finally decided to proceed with enclosed bridges on the *Endeavour* Class vessels. There was a caveat however, that they either be fitted with an opening window or a door on each of the bridge wings so that the Master could get a feel for the wind. As it turned out both of these options had to be abandoned because of the slope (25°) of the windows.

Since entering service we've heard nothing except extremely positive feedback from our crews regarding enclosed bridges. We've also heard one anecdote regarding a pilot who needed to move from the center console to the bridge wing for the docking operation in Valdez. It seems the pilot proceeded to put on his winter coat, gloves, and when he got to his hat, was asked by the ship's Master where he was going. At that point the pilot remembered they docked the *Polar Endeavour* from the inside.

Integrated Bridge

Navigation and Bridge Control

The integrated bridge, Figures 41 and 42, was designed and built to meet the requirements of ABS' *Guide for Bridge Design and Navigational Equipment/Systems (NIBS)* and to meet Polar Tanker's requirements for operating in the North Pacific/Gulf of Alaska environment [36]. The vessels are being built with a fully enclosed bridge that extends the full beam to one meter past the maximum beam of the vessel on each bridge wing. The decision to enclose the bridge wings was based on operability concerns resulting from the ergonomics of "open" bridges and the need to protect the bridge electronics. Operation of the vessel is centered at the bridge console where all electronics are fully integrated. The integrated bridge, built by Raytheon Marine, includes a fully redundant bus design to ensure availability of all navigation equipment in case of any single bus or component failure.

The integrated bridge is equipped with an Automatic Navigation and Tracking System (ANTS) designed in accordance with DNV Watch One requirements. The ANTS system will steer automatically according to a programmed course when the autopilot is engaged. It will also monitor the course and will alert the operator should the vessel deviate from the prescribed course more than the allotted amount. The ANTS system is equipped with a fully adaptive autopilot.

Important to the bridge design is the center console, the two wing consoles, the GMDSS station and the navigation planning station. The center console is setup similar to an aircraft cockpit. The navigation officer sits immediately to the left of the center section of the console, immediately in front of his control location is an ARPA radar, and controls

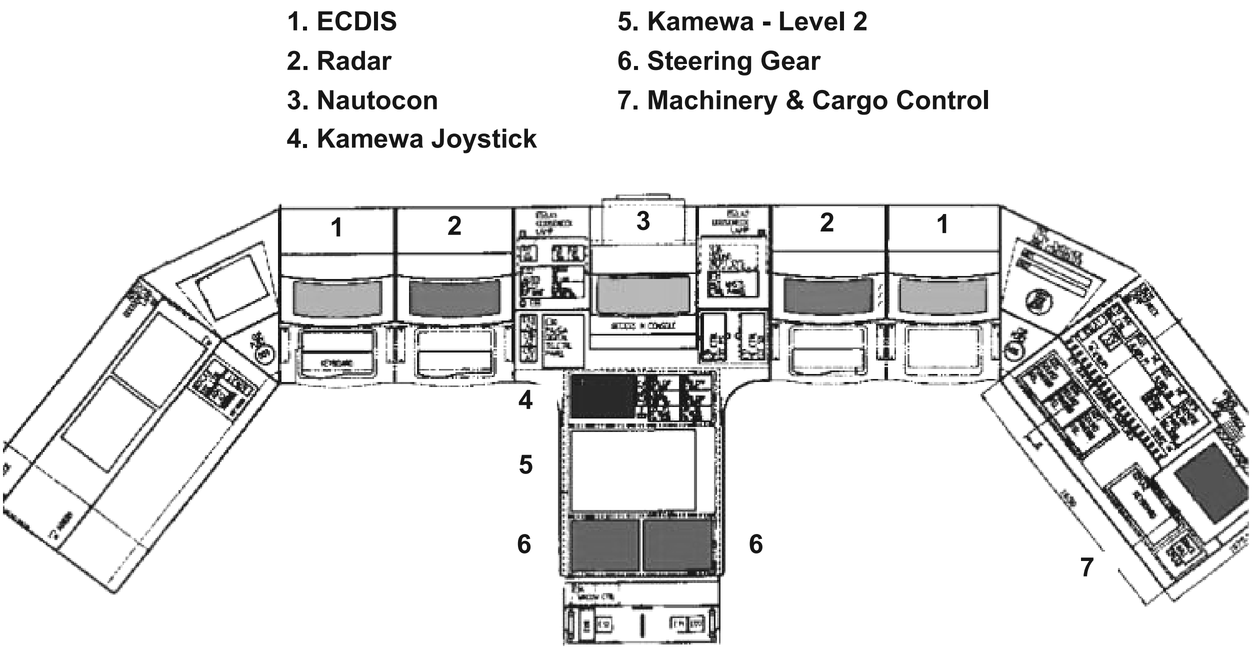


Fig. 41 Layout of integrated bridge equipment

Fig. 42 *Endeavour* Class integrated bridge

for the ANTS autopilot and its overrides. To the left is the ECDIS master console, and to the right the Nautoconning navigation information display. On the center section to his left are controls for the Hull Monitoring System, navigation lights, radios, and echo depth sounder. In the center console are the Level I, II, III and IV controls for the Kamewa controllable pitch propellers, rudders and bow thruster, as well as the helmsman's station. On the right side of the center console the navigation controls are duplicated in a near mirror image with an ARPA radar before the chair, then an ECDIS slave immediately to the right. The right wing portion of the center console houses GMDSS radio controls, clock controls, CCTV controls, as well as engine controls and the ABB operator's station.

As part of the bridge enclosure process it was decided that for the able-bodied seaman (AB) watch stander to remain an effective part of the bridge team, at sea, their position needed to be upgraded. Polar ABs had long been part of all bridge team management training; they had not however, qualified for ARPA training. It was decided that with the new Integrated Bridge and what was envisioned for further advancements in our Bridge Team Management program, that the AB watch standers all needed to be ARPA qualified. The first group of ABs was trained with the help of a senior Master from the *Polar Endeavour*. This group completed the course successfully, and gratefully. The program is viewed as a success both on the part of management and on the part of personnel.

Behind the center console are the GMDSS radio station and the navigation plotting station. The navigation plotting station is fitted with an independent ECDIS that can be used for route planning. This ECDIS can serve as a spare to the main ECDIS in the event of a failure except for replacing the ANTS. Normal course tracking must be used when on the backup ECDIS. Both ECDIS are fitted with special prediction software from SSPA that combines wind, propeller, GPS, bow thruster, etc. data and predicts where the vessel will be. This software is considerably more accurate then dead reckoning programs previously used.

The navigation plotting station was originally fitted with one DGPS and two ADSSE transceivers, which were capable of receiving both GPS and GLONASS signals. The ADSSE transceivers provide positioning data at sea and positioning and movement data to the Valdez, Alaska Vessel Traffic System (VTS) in Prince William Sound. ADSSE is a requirement of 33 CFR §165.1703(c)(6) as legislated by OPA90. With the promulgation of the SOLAS requirement for ships to be provided with Automatic Identification System (AIS) equipment, it was decided that the DGPS would be upgraded to an AIS system, and that one of the ADSSE transceivers would be changed out in favor of an AIS system. The one remaining ADSSE transceiver is to remain, first to assure compliance with the USCG VTS until such time as the AIS system in Prince William Sound is fully functional. Second, even after the AIS system is in operation, the ADSSE's GPS/GLONASS receiver will be retained because it provides the vessel with its second means of electronic positioning.

Each bridge wing is fitted with a control station for docking and undocking the ship. These stations have both Level I and Level II Kamewa controls, and the *Polar Endeavour* was fitted with a single 27" high-resolution monitor capable of switching between the Nautoconning display or the ECDIS display. As installed on the *Polar Endeavour* the console was a total success for docking and undocking. A much higher degree of control was achievable, and at the same time much quicker docking and undocking times were being achieved. What was found was the consoles were not particularly user friendly. The Level I controls were too far away from the window and that when forced into the choice between Nautoconning and ECDIS displays, the Nautoconning display was most often used. This meant the predictor software wasn't being used.

It was found that the having radar displays on the wing consoles would enhance safety when embarking and disembarking pilots. Between the *Polar Endeavour* and the *Polar Resolution* the console was redesigned, the console was shortened, moving the Level I control forward against the window. The 27" high resolution monitor was replaced with two 17" flat screens. Each flat screen is now able to display not only the Nautoconning and ECDIS displays but also both 3 and 10 cm radar displays. This change has resolved all issues with bridge wing console use.

Joystick

In developing the bridge design, careful consideration was given to facilitating operations. Close attention was paid to both ease of operation and redundancy in control. As a result of design efforts, the bridge is fitted with Kamewa CANMAN® controls. The controls feature a fully integrated joystick, Figure 43, that is capable of controlling both rudders, both controllable pitch propellers, and the bow thruster from a single lever. The single joystick may be operated in an at sea mode where it operates the propellers as a throttle and the rudders as a helm lever. It may be operated in a docking mode where the rudders, propellers and bow thruster are activated in a "point and shoot" methodology. The joystick is also capable of adjusting the center-of-pivot from the bow to midship to the stern. This first level of controls is commonly referred to us as Level I controls.

Fig. 43 Kamewa joystick control (Level I)

A second level of control, utilizing individual controls for the two propellers and rudders, as well as the bow thruster is also installed. The second level consists of a port and starboard joystick with throttle and steering control, and a bow thruster lever control. We commonly refer to this as Level II control.

In addition, for steering, a fully adaptive autopilot, follow-up helm lever (Level III), and non-follow-up controls (Level IV) are installed. When in ANTS control, follow-up override tillers are available at the port ECDIS and next to the port radar. For throttle control, pitch can be changed through the CANMAN® system (Level III) and there is an engine order telegraph installed (Level IV).

One common complaint our crews have had about the joysticks, since the beginning, is that they are not electroshaft (servo-motor) controlled. When the pitch and rpm is varied the controls in the engine room automatically move to indicate the variation. The same is not true on the bridge. While control position can be followed when someone is working in Level II at the center console, it is very difficult to follow when someone is working in Level I. It is almost impossible to follow if the vessel is in a docking mode with control on the bridge wing. A mate must follow the indicators for the bow thruster, the two propellers, and the two rudders simultaneously in order to tell what is happening. There is no way to predict what was ordered.

Based on our requests, Kamewa has been working with us for the past two years to develop an electroshaft control to replace the existing units. Kamewa had electroshafts from other services, which our operators felt were not as ergonomic as the original designs. We expect to see the first prototype by the end of 2003.

ACCOMMODATIONS

Any discussion of the *Endeavour* Class vessels must include the accommodations. From the exterior only the wheelhouse, which has been discussed in detail earlier, indicates any difference from any other vessel. Once inside, the accommodations offer insights into changes to an ever evolving culture. Changes that Polar made with full concurrence of Company management, the Officer's Association and the Employee's Union.

History

The segregation of Officer's and crew on ships has probably existed, as long as there have been ships. The segregation of deck and engine officers has probably existed ever since they started fitting engines in ships. For Atlantic Refining (ARCO Marine's predecessor company) the segregation of the deck and engine departments started with the two island ships with the deck officers and the able-bodied and ordinary seaman forward, and the engineers, firemen, oilers, and everyone else aft. When the forward house moved aft the segregation continued. The first ships had a deck with the Master and the Radio Officer, a second with the deck officers, a third with the engineering officers and the rest of the crew resided on the remaining decks. In the next generation of ships the segregation still existed; it was much the same, only slightly different. This time the deck department occupied one deck, the engineering department another, and everyone else the remaining decks.

Lounges, laundries, and messes were segregated by officers and crew. It was not uncommon to have tables in the officers' messes with four place settings (i.e., Master, Chief Mate, Second Mate, Third Mate). You ate at your assigned seat, without deviation. On ships with long tables again there was assigned seating according to position. Shore staff and visitors were directed to empty seats. Seating in the crews' mess for other than unlicensed personnel was by invitation, often with raised eyebrows. Lounges provided one of the few inner sanctums, other than a private cabin, where crew could socialize away from the public. But even then, the crew and officers generally socialized in separate lounges.

Philosophy

In the mid to late 1980's ARCO Marine began its bridge and engineering team management training programs. This program focused on a philosophy of equalizing the roles and impact each person had in emergency situations. As this program matured management also realized that there were some anomalies in the philosophies they were touting in that they were looking for an equalizing in roles and impact, while at the same time openly segregating by working group (deck and engine) or by class (licensed and unlicensed). To this end the naval architects were tasked to make the following changes to the accommodations for the *Endeavour* Class vessels:

- Equalize rooms – same rooms for officers and crew
- Separate crew spaces from public spaces
- Eliminate Officer/Unlicensed segregations
- Institute No Smoking Policy
- Provide onboard computer based training facilities
- Improve sound and noise isolation
- Improve lighting

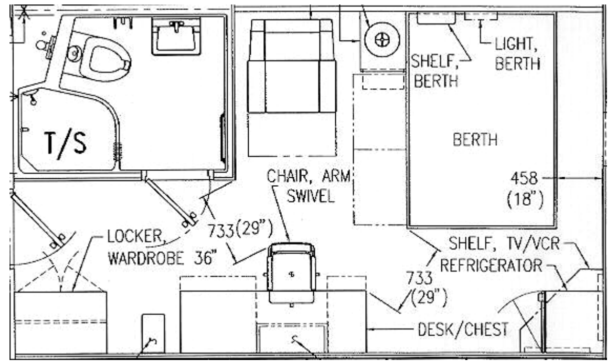


Fig. 44 Typical cabin

Rooms

It was Polar's intent to make all rooms identical, junior officers and crew. This was done as much as possible. There are variances between rooms as a result of structural differences in the steel structure, as opposed to joiner work. Figure 44 shows a typical cabin. Each cabin has its own private toilet/shower, a double bed, recliner, wardrobe, dresser, desk, desk chair, radio shelf with radio, TV/VCR, refrigerator, and nightstand. The officer's cabins are dedicated because of watch call equipment installations, and the Steward's cabin is assigned because of a LAN installation. Other than that all crew cabins are identical. The Master and Chief Engineer do have offices, day rooms and bedrooms. However, they have identical toilet/showers and beds.

To encourage the removal of some of the long, standing barriers between the Engineering and Deck departments it was decided that some innovated ideas would be tried. The first was to have the Chief Mate and the First Engineer share an office. The Mate and First's cabins are identical to the crews except they don't have desks; instead there are doors, which lead to the shared office. One advantage that has been found to this arrangement is that the Mate and First Engineer are in much closer contact, facilitating discussions on work that needs to be done.

The second experiment was to put the Master and the Chief Engineer on the same deck, by themselves, and to place a door between their offices. To date I've heard mixed reactions. I've heard some Chiefs act no differently then when their cabins were two decks below. I've heard that others keep the door open and the conversations run freely. This is something that is most likely a function of individual personalities. The presence of the proximity of the rooms and the presence of the door will help, but it can't cure the problem if there is a lack of communication.

Crew/Public Decks

The *Endeavour* Class accommodations are laid out so that the when in Port the Public (i.e., contractors, port personnel, shore personnel, etc.) need only have access to the Upper and "A" decks. "B", "C", "D", and the Wheelhouse remain off limits. The exception would be, those having business to do with the Chief or Master on "D" deck or having to do maintenance in the Wheelhouse.

The Upper Deck on the *Endeavour* Class vessels has men's and women's change rooms, hospital and a riding crew room as well as number of utility spaces. "A" deck has the Cargo Control Room, Mess, Conference Room, Training Room, Library, Gymnasium, Smoking Lounge, and Galley. These spaces are considered "public".

Of interest, all crew, licensed and unlicensed, participate in the cleaning of the vessels and in the polishing of the decks. Access to the "private" decks on the *Endeavour* Class vessels may not be done in work clothes. If a crewmember has to make a quick sojourn to his cabin and they do not want to change, surgical booties are required. The same is true of shore visitors.

Public Spaces

Riding Crew

The *Endeavour* Class tankers were equipped with a single riding crew room capable of holding six in three bunk beds. The room is fitted with two toilets. At the time of design it was determined that because of the proximity of the change rooms the riding crew could use the showers in the change rooms rather than duplicate facilities. At those times the riding crew rooms are full, this proves to be a burden. In hindsight, the riding crew rooms should have been fitted with individual showers. This would allow for better segregation for a riding crew and would ease the strain on the change rooms at times when the vessels are carrying maximum crews (i.e., when cleaning for shipyard).

Change Rooms

Providing change rooms was somewhat of an experiment based on the European method of operating tankers. The European ships all have change rooms and the crew never carries engine room or tank dirt with them into the accommodation block. On the other hand, U.S. ships almost never had change rooms, and crews were expected to change in their cabins. As part of the isolation of crew spaces from the working and public spaces change rooms were provided. Each change room was provided with a locker room area and a shower area.

The concept of the change room is very good and has been very well received. It has been found that it is not practical to limit dirty clothes to the Upper Deck level, that "A" deck level is more practical. Dirty clothes are not tolerated above "A". It was found that the men's locker room is too small and the women's is too large. This of course is subject to the crew mix at any given time. If we were designing the locker rooms again I would look at the riding crew room to see if it was possible to compact it into a "minimum" area in order to expand the men's locker room as much as possible. In other comments we received was a recommendation to have a dedicated "oily" clothes washer and dryer in the locker rooms so as not to bring dirty clothes back into the house, when they need washing.

Conference Room

Historically none of our ships have been fitted with conference rooms. When meetings needed to be held lounges were commandeered. If someone was watching a movie or reading, it was too bad. When we went to shipyards no matter how much protection was placed on the furniture, invariably someone would have a screwdriver or other tool in their pocket, which would end up tearing the upholstery.

In designing the *Endeavour* Class tankers it was decided there would be a dedicated conference room for meetings. This room would serve for meetings; safety, maintenance, human relations, etc. The room would be equipped with white boards and a TV/VCR for training videos. During shipyard periods, shipyard meetings would be held in the conference room rather than in the lounges. At worst a chair would be damaged rather than a sofa or a recliner. Carpeting was no longer at risk, since the deck in the conference room is linoleum.

The conference room has proven to be a better benefit than anyone ever expected. The room is used for all the anticipated meetings. It was the unanticipated meetings that surprised us. Starting within the first days out of the shipyard the conference room began being used daily. Each day the maintenance crew and the officers gather first thing in the morning and list the daily maintenance work on the white board. Assignments are made, work is divided, and as work is completed people return to find out what is next on the list. This daily use has made it a favorite location with the crew.

Mess

The introduction of a single mess for officers and crew initially brought comments ranging from "it's about time" to "if they do that it's time for me to retire." After a year and a half of service the single mess is alive and well, and is one of the better advancements that have been made in our fleet.

Initially the mess was to have had seating for 32 at eight tables each seating four. This arrangement was rejected by the officers as being no better than having two separate messes. They felt that ultimately the crew would migrate to tables as far apart as possible from the officers, and that in some cases the deck and engine officers would separate. Ultimately two long tables of 16 were fitted. Although not capable of serving all crew in a single serving it is possible most of the time to get everyone to one table. One comment that did return after the *Polar Endeavour* left was that the 2 m space that was left between the tables was too large and that a 1 m space was more than sufficient.

Lounge

Like the mess a single lounge was thought to be an issue of concern, but not as great as with the mess. With the advent of small TVs and personal VCRs, over time the crew congregated less and less in the lounges and spent more and more of their free time in their rooms. The single lounge in effect brought no real comments one way or the other.

In service the single lounge seems to have had the exact opposite effect as what might have been expected. Each cabin on the *Endeavour* Class vessels is fitted with a TV/VCR which is connected to the ship's AM/FM/Antenna system which allows it to receive to satellite stations, one as selected by the Master and one as selected in the lounge. Yet, it is reported that the lounge is once again being used as a meeting place for watching movies as a group. Where for many years, everyone went their separate ways, they are starting to come back together again.

It cannot go without mentioning that the *Endeavour* Class vessels are smoke free with the exception of a small smoking lounge located on the "A" deck. This concept was presented early in the design stages and was accepted readily, without comment. Since implementation there have been no adverse comments. In general, the non-smokers have been very happy, and the smokers have been able to get along.

Sound and Noise

At the time the Specifications were written for the *Endeavour* Class vessels our knowledge of sound and noise standards was non-existent. Historically, we relied on the shipyard and the joiner contractor to select materials that would provide accommodations that would be suitable for the crew. Recognizing that additional effort had to be made to limit noise exposure we did include IMO Resolution A.468 (XII) "Code on Nose Levels On-Board Ships" as a Specification requirement. We also included this somewhat cryptic phrase in the Specifications: "The acoustic properties of joiner bulkheads between adjoining living spaces shall be such as to prevent transmission of noise associated with normal levels of conversation, radio and television reception and personal activity in adjacent spaces."

For future projects three changes would be made to the approach to accommodation sound and noise. First, the accommodation block would be treated in the same manner as passenger quarters on cruise vessels. Second, it would be ensured that the space between the deck and the false ceilings would be considered with regards to sound insulation. On the *Endeavour* Class vessels many joiner bulkheads stopped at the ceiling, leaving an open void between rooms. Third, the Machinery Control Rooms would be treated as joiner spaces. Although the rooms are quiet, a false ceiling and joiner bulkheads would have further improved sound insulation.

Lighting

Historically, lighting has been one area where Polar has had the greatest number of crew complaints, particularly with respect to deck lighting. Luckily, lighting quality is easily fixed by including the right requirements in the Specifications. The required average illumination levels, not including a 0.70 maintenance factor, are shown in Table 9.

We have had no complaints and only positive feedback about the lighting levels on the *Endeavour* class vessels. The lighting levels are consistent with our desire to never hear another complaint regarding lighting.

Table 9 - Lighting Requirements

AREA	**Average Illumination (Foot Candles)**
• Wheelhouse • Machinery Control Room • Cargo Control Room • Machinery Spaces • Inert Gas Generator Room • Cargo Pump Room • Electronic Equipment Rooms • Training Library • Dayrooms • Serving Area • Hospital • Change Room • Toilets • Staterooms • Baths	20
• Cargo Manifold • Mooring Stations	15
• Upper Deck (Cargo Block Area) • Incinerator Room • Battery Room • CO_2 Room • Foam Room • Hydraulic Room • Elevator Machinery Room • LAN/UPS Room • Garbage Room • Medical Locker • Riding Crew Berthing • Slop Chest	10
• Unassigned	5

MANNING

The immediate reaction to having a ship with two engine rooms and with the high degree of sophistication that the *Endeavour* Class vessels have is that crew size would increase over what had been our normal manning levels. From the onset our goal was to choose equipment and to design the vessel so as to minimize manning requirements. As we developed manning requirements we worked closely with the U.S. Coast Guard in New Orleans to establish a manning scheme that was not only suitable for our needs, but was acceptable for meeting regulatory requirements.

The *Endeavour* Class vessels have accommodations for 32, six of which are in a riding crew room. So, actual crew size is limited to 26. Because we were operating with crews of 22 on existing ships, we were confident that room for a 26-person crew was more than adequate.

In determining manning requirements we sought the Coast Guard's concurrence in providing a maintenance gang rather than a conventional arrangement of having 3 Ordinary Seaman and 3

Qualified Members of the Engineering Department (QMED).

Ultimately the Certificate of Inspection (CoI) calls for a crew of 20; eight officers (Master, Chief Mate, Second Mate, Third Mate, Chief Engineer, First Assistant Engineer, Second Assistant Engineer, Third Assistant Engineer), three Able Bodied Seaman, six Maintenance personnel, plus 3 other persons in the crew (Steward, Cook/Baker and Messperson). The Maintenance personnel must consist of at least three individuals holding QMED ratings with endorsements as Junior Engineers or Oilers and at least three individuals holding Ordinary Seaman endorsements.

Polar took it upon itself, because of the sophistication of the navigation equipment to require that the Able Bodied Seaman have RADAR/ARPA endorsements.

The Endeavour Class is currently carrying 21 crewmembers and occasionally carries 22 in the crew. In addition to the above listing of crewmembers, the new vessels generally carry an additional Third Mate to ensure compliance with OPA90 requirements for work time. The need for the additional Third Mate is a result of the ship's trading patterns, as opposed to unexpected work as a result of faulty design. As needed, depending on special maintenance projects, an additional Third Assistant Engineer may also be added.

COATINGS

Concluding a paper on the *Endeavour* Class tankers without mentioning coatings would be somewhat of an injustice, particularly in light of the rubbish that has been spread in the press by purported experts with little or no background or knowledge of tankers or tank coatings. The *Endeavour* Class tankers were coated in accordance to a very careful plan based on 20 years of knowledge, at the time, of operating in the Alaskan trade.

General

Coatings, particularly ballast and cargo tank, are significant contributors to the life, health and longevity of a vessel. They play a major role in the maintenance costs and because of this they were a major focus of attention during the development of the Specifications for the *Endeavour* Class vessels. In developing the Specifications, Polar was careful to limit paint suppliers and products to those, which it had tested in ARCO's laboratories and in field-testing. Polar also made sure that the Specifications were consistent with recommendations of the Society for Protective Coatings (SSPC) and their own experiences. Polar's Specifications with regards to paint were very specific and offered little or no latitude for change. However, Polar was willing to listen to proposals from both Avondale and International Paint Company, the ultimate supplier, with regards to betterments.

Tank Coatings

Tank coating application is a relatively simple process. If you follow the manufacturer's recommendations the coatings will be good. If you don't you will ultimately have problems. The manufacturer's recommendations are well written, generally at a ninth grade or lower level so that they are easy to understand. In our case, we have our own full time paint inspector and two International Paint inspectors that report directly to us on site. Still, it is often times hard to get people to follow directions.

Prior to signing the construction Contract with Avondale, we met with Avondale senior production officials to discuss the painting of ship's tanks, specifically cargo and ballast tanks. At issue was how to paint tanks, which were to be built of 150-ton units over a period that would span close to 12 months (note: the time span has actually run about 19 months). After a reasonable discussion it was determined that the only practical way was to paint the tanks when they were complete, rather than in the blast house as each individual unit was completed. The cure time of epoxy paints and the physical damage of assembly made painting in the blast house and localized repair impractical.

Our Specification requires that for tanks all edges be rounded to a 2 mm radius, that all weld spatters be removed and that they be blasted to a near white metal (SSPC SP-10). The 2 mm radius is usually achieved by edge grinding. However, care must be given to assure that it is indeed round and that sharper edges are not introduced.

Now, with that said, over the last four years we've seen numerous failures in the painting process. When directions are followed we've had no problems, when they are not we've seen many. Here are some of the causes of problems:

- Unclean surfaces prior to painting (i.e., dust/rust blooms)
- Securing dehydration units at night or on weekends or between paint coats
- Inadequate ventilation (i.e., air changes)
- Securing ventilation over weekends
- Too thick an application of paint in a single coat (i.e., up to 24 mil. wet film)
- Too long between coats (i.e., 9 day window expires)
- Full coat used rather than tie coat (i.e., to make up for 9 day window full spray, results in over millage, poor curing)

- Too thick a total application of paint for all coats (i.e., up to 85 mil. dry film vs. specified 16 mil.)
- Poor mixing
- Improper use of solvents/thinners
- Improper use of nozzles
- Poor spray techniques
- Too sharp (<2mm) radii
- Weld spatter
- Pin holes

Cargo Tanks

With over 24 years of operation in the Alaskan trade we've found that corrosion in the cargo tanks is limited to the tank bottoms. On two ships that entered service in 1978 and 1979 there is virtually no corrosion in the overheads, the same is true of a third, which entered service in 1982. None of these three ships had their cargo tanks coated when they were built. The first two carry ballast water regularly in the cargo tanks, whereas the third does not. We attribute this lack of corrosion in the overheads to the fact that ANS crude is waxy, and the structure gains some protection from the wax. Moisture is not able to stay in contact long enough to corrode the structure, so loss of steel is not known. Because of this there is no reason to coat the overheads of the cargo tanks. It should be noted that coating tank overheads was discussed, but the burden of maintaining a coating system to assure failures do not result in structural cracks (i.e., corrosion concentrates in areas where coatings fail) was not warranted. In the end, ANS trade tankers do not have the same problems that other tankers have, and do not require the same treatments.

Bottom corrosion is a different story. In recent years bottom corrosion has been attributed to microbial blooms. But, as an operator we've been well aware of the problem since our 190,000 DWT tankers first entered service in the winter of 1978. At that time we discovered pits, ranging from 6 mm to 12 mm in diameter and up to 6 mm deep. The pits were generally filled with a grayish colored water, which when rubbed would polish the steel in the bottom of the pit to a shinny silver color. At the time there were theories of microbial action, hydrogen sulfides, and sulfuric acids, but being good ship operators we took the easy way out and painted the bottoms of the tanks with two coats of epoxy paint. For the last twenty years, two coats epoxy on the bottom surface and up 400 mm on the vertical surfaces has been the proven solution for us.

The original Specification called for International Interline 604 for coating the cargo and slop tanks. This is conventional epoxy paint. Before starting the cargo tank coating on the third ship, the shipyard and International Paint came to us proposing that we upgrade from Interline 604 (80% solids) to Interline 925 a 100% solids paint. We had used 925 on three tanks on the *Polar Resolution* after experiencing some paint failures. The 925, when applied according to directions provides an excellent coating. Interline 925 has been accepted as a substitute for Interline 604 for the cargo tanks on the last three hulls.

Ballast Tanks

The ballast tanks on the *Endeavour* Class tankers hold approximately 62,362 m^3 of ballast (100% capacity). The tanks vary from the openness of the 3 m wing walls and double bottoms, to the mazes of the after trim tanks. The structure is filled with brackets, headers, rat holes, cut outs, collars, etc. that make painting a nightmare. The Specification was written and the paint was selected based on painting the ballast tanks once at mid-life of the vessel, or 15 years after first entering service. International Paint has provided a 5-year warranty on the coatings. Our belief being that if the paint is good for 5 years it will be good for 15. After the first year of service on the *Polar Endeavour* we've heard no reports of paint failures.

As mentioned earlier the ballast tanks are prepared with a 2 mm radius on all structure and all weld spatter is removed. The tanks are then blasted to a near white blast (SP-10) and cleaned for inspection. After passing inspection the tanks receive their first coat of International Intergard 403. The tank is inspected at this time to see the first coat is proper. This coat of paint is followed by two stripe coats, one hand and one spray, and then a final spray coat is applied. At this point a final inspection is held. This process has proven to be very successful.

Final Comments on Tank Coatings

One of the biggest problems we've had with coatings has come not from the painters, but from the damage done after the painters have finished their work. The Far Eastern and European yards all build around a schedule that calls for delivery within days of completion of the tanks. For our vessels the time between the "final" paint inspection and the delivery can be 6 to 8 months. During this time the tanks are not locked and the tanks are not isolated from hot work and outside damage. This damage has had a great impact on the paint. To date we've not seen any failures in service as a result. But it would not be a surprise if there were.

Anti-foul

Polar made a decision that the *Endeavour* Class vessels would not be painted with TBT containing paints, although the original Specifications did call for them. At the time we were somewhat limited in alternatives, as the EPA had not yet approved International Paint's Ecoloflex for domestic use. As a result we painted the *Polar Endeavour with* International's Interspeed BRA 640 CDP and received permission from the EPA to put a test patch of Ecoloflex on the *Polar Endeavour*. International Paint, in fairness to them, did advise us that the CDP was a lesser quality paint than what we were used to and that they fully expected that we would have less than satisfactory results. After less than a year of service the CDP had a full growth of grass, which had to be scrubbed, which was not surprising. What was surprising was that the test patch of Ecoloflex faired no better. While part of the growth was attributed to the paint we also discovered that we were getting cracks similar in appearance to dried earth in a drought. The cracks in turn provide a place where microorganisms can grow. These microorganisms provide nutrients for grass growth. It has been determined that the cracking is a result of the prolonged periods of time the anti-foul paints are left in fresh water.

We are currently working with International regarding the possibility of painting the third ship, *Polar Discovery*, and the remaining vessels with either International Paint's Intersleek or with Ecoloflex using a different application scheme. We are currently costing a change order to upgrade the bottom paint.

As an aside, for the last 20 years we have not painted the flat bottoms of our vessels with anti-foul paint. We've had little or no growth that has warranted the application and maintenance of bottom paint on the flats, other than anti-corrosives. In the past two years there has been an increase in the appearance of small barnacles, which has prompted us to rethink our position.

CONCLUSION

If this paper reads somewhat like a primer for a naval architecture/marine engineering design class, it should. We were given what for me will most likely be a once in a career opportunity to design a tanker as I was taught in college. We were allowed to follow the design spiral as it took us through the revolutions. For the first time in my professional career engineering decisions for ship construction were being made by Owner/Operator and not by the Shipyard or worse yet the bean counters.

Some will argue that the cost of the ships was excessive. Jones Act ships or any ship built in the United States is expensive when compared on a world basis. However, much of the cost of these ships lies in the detail of the structure, which is not included in foreign construction, and in the redundant propulsion plants. Granted, the cost will never equal the cost in the Far East yards, but the differential is probably not as excessive as some would like to believe.

The point here is not the cost of ships. The point is that ships, be they built in the Far East, Europe, or the United States are expensive. They represent significant capital investments by the Owners. Our total engineering investment at the start of this project was approximately $2.5 million, roughly 0.6% of the initial two ships construction cost. Model tests results produced savings of over 6%, improvements in plant design, and other changes adds an additional 4% to the improvement total. Selection of equipment to reduce maintenance is already showing considerable paybacks. The ability to improve ergonomics and to satisfy crew wishes is priceless. The results of these efforts are shown in the fact that in the first 29 months of operation the *Polar Endeavour* and the *Polar Resolution*, together, have only experienced 12 hours of unscheduled down time.

I hope that both students and working engineers that have taken the time to read this paper have reflected back and realized, that the *Endeavour* Class tankers are living proof that the ideas laid out in *Principles of Naval Architecture*, *Ship Design and Construction* and *Marine Engineering* and in your college design courses do exist, and they do work!

ACKNOWLEDGEMENTS

I'd like to acknowledge the people of ARCO Marine and Polar Tankers who have taken the time to talk to me, or someone involved with this project to pass on their thoughts and ideas. It is these thoughts and ideas that have been incorporated in the design of these exquisite ships. Each of you should take pride when you look at the ship and claim proudly you'd passed on your ideas to the designers, and they were heard.

I'd like to thank all the people that have worked in our offices in Avondale, particularly those who have been there on a permanent basis. It has been a long and grueling project that has tried our mettle. We can be proud of our accomplishment. Without all of us the *Endeavour* Class tankers don't exist, as we know them. In particular I'd like to recognize James Read, Francis Iwancio, and William Croke who have been together with me since the start of this project, and William Young and Dave Jones our two senior steel inspectors.

To the many consultants and contractors who have given considerable efforts, these efforts have not gone unnoticed. We have come to rely on your expertise to help us with our shortcomings and to depend on you for both engineering and moral support.

I'd also like to acknowledge the working men and women of Northrop Grumman Ship Systems Avondale Operations and its sister operations, who toil daily in the heat and humidity of the Gulf Coast. Building ships under these conditions is no easy task. Building fine ships is an indication of their personal dedication.

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