

USCG Polar Class Aft Sterntube Bearing Design Modifications

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ABSTRACT

The U.S. Coast Guard (USCG) operates two Polar Class Icebreakers, the POLAR SEA and POLAR STAR. They have a length of 399 feet and a displacement of 13,500 tons, and are also the most powerful non-nuclear icebreakers in the world, with a maximum rating of 3 x 20,000 shaft horsepower. Each propeller shaft is supported by two water lubricated sterntube bearings. The bearings are a dove-tail slot stave design. Both the aft and forward bearing materials are Thordon XL (Polymer Alloy). The bearing housings are supported by five lands that are integral with the stern bossing. The severe operating environment has caused erosion to the lands due to fretting and corrosion resulting in insufficient support of the bearing housing. Because of concerns about welding on the large HY-80 casting previous efforts to restore fit of the bearing housings has relied on build up of the lands with Belzona Super Metal (a machinable grade metallic polymer). For this application the lands have been repeatedly undercut and boring undertaken to restore fit. Using this method of repair has proven to be short lived and expensive to maintain. A project was undertaken to develop a permanent repair and/or redesign that would effectively address the loss of fit as well as provide for a reliable bearing. The bearing design arrangement was examined, with particular attention to considerations for ice-class service. The properties of potential chocking and bearing materials were assessed. Modifications to the bossing and bearing length were also examined. This paper presents the results of the study.

INTRODUCTION

The propulsion systems on the Polar Class vessels consists of three controllable pitch propellers each driven by either a Diesel-Electric (6,000 HP) or Gas Turbine (20000 HP) [CODOG]. Both the aft and forward bearing materials are a "polymer alloy" (Thordon XL). The bearing housings are supported by lands (rings) – five (5) for the aft sterntube bearing and four (4) lands in the forward sterntube bearing.

The fit of the bearing housings to the lands in the aft stern tube has been lost. The forward bearing on the wing shafts (not subject to this study) had similar problems that were addressed by welding in new land rings. Since the aft stern tube bearing is supported in lands which are part of the stern frame (a HY-80 casting) a similar repair was not considered practical. Since 1992, the land rings have been "built up" by applying a metallic polymer. For this application the lands have been repeatedly undercut and boring undertaken to restore fit. Using this method of repair has proven to be short lived and expensive to maintain. To date the aft stern tube lands have been serrated and undercut approximately 13 mm to accommodate the metallic polymer layer.

The loss of fit between the bearing housing and the lands is the result of erosion. Erosion has been caused by corrosion and fretting. Although painted prior to installation of the bearings, the lands have been exposed to seawater intrusion since the fit is not water-tight. The severe dynamic loading of a Polar class propulsion system and the clearance provided by the locational fit of the bearing housing has likely produced a fretting action which further deteriorates the fit. Photo 1 shows the erosion/corrosion of the aft land in the center aft sterntube bossing.

A project was undertaken to develop a permanent repair and/or redesign that prevent the loss of fit between the bearing housing and the stern frame casting / lands, as well provide for a reliable bearing. The USCG had requested that the study focus on the potential of chocking the bearing housing in permanently with a suitable bedding material. The bearing design arrangement was also examined

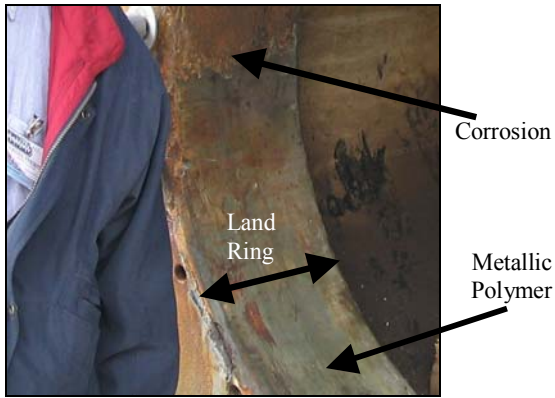


Photo 1 - Aft Sterntube Bossing and Lands

SHAFTLINE DESCRIPTION

The vessel has a triple screw propeller configuration. Each of the 4 bladed controllable pitch propellers are directly driven by either a DC Motor (6,000 HP), or a Gas Turbine (20,000 HP) [CODOG]. The wing propeller shafts are 17.5 m long, each supported by two sterntube bearings. The center shaft is 21.5 m long and is supported by one aft sterntube bearing and one split roller bearing just forward of the sterntube seal. The oil distribution shaft, for the controllable pitch propeller, is located between the DC Motor and the sterntube seal on all shafts. The main thrust bearing is aft of the DC Motor on the wing shafts and aft of the main reduction gearing on the center shaftline. There is an intermediate shaft between the DC Motor and reduction gear on the center shafting with a support bearing at the forward end. A schematic of the propulsion shafting is shown in Figures 1 and 2. Photo 2 shows a view of the Polar Sea stern when in dock. A wing propeller shaft is shown in Photo 3, and an aft sterntube bearing housing is shown in Photo 4.

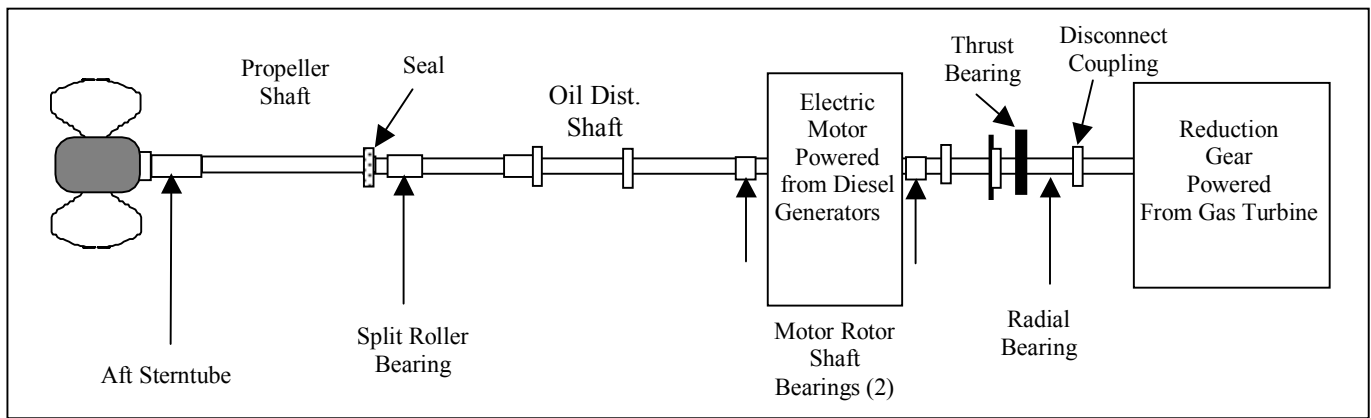


Figure 1 - Schematic of Center Shaft

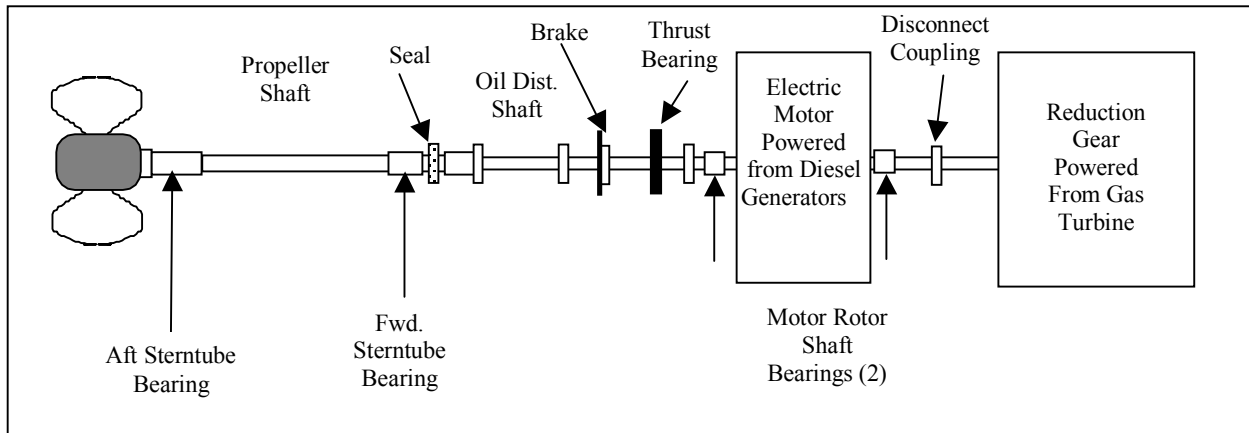


Figure 2 - Schematic of Wing Shaft

DESIGN CONSIDERATIONS FOR ICE CLASS STERN TUBE BEARINGS

Ice class stern tube bearings are subjected to high dynamic loads during ice-propeller interaction [Cowper and Kolomojcev 1997]. These loads result in high dynamic pressures on localized areas of the bearing, as well as shaft displacements that can exceed the clearances within the bearing. During ice-propeller interaction, only a portion of the bearing can be loaded (i.e., < 50% of the length), with a highly concentrated pressure that acts on less than 25% of the bearing length that moves forward and aft along the bearing length. This can be characterized by a “rocking or bending” motion of the shaft due to the ice forces on the propeller. Under certain conditions the propeller weight can also be completely supported by the ice then suddenly released, resulting in the shaft essentially being “dropped” down on the bearing. It is estimated that bearings on the USCG Polar Class can experience a maximum localized pressure of 8.3 MPa, and a dynamic load of 2.5 MN (~3.6 times the static load). Ice class stern tube bearings should include the following design features:

- Solid support such as interference fit or chocking of entire bearing housing in bossing.
- It is beneficial for the stiffness of each component to increase from the bearing surface through to the bossing structure, particularly for this application. This in general requires the elastic modulus of bearing material to be less than the chocking material and the chocking material elastic modulus to be less than the bossing structure.
- Bearing assembly should be designed to withstand high pressures and shock loads that are produced during ice-propeller interaction, as described above.
- Bearing material should distribute the dynamic loads to reduce localized pressure as much as possible, while maintaining shape and lubrication.
- Allowance should be made for axial pressures present in the bearing and chocking materials, such that they are not confined axially.
- The deflection of the bossing is less than the bearing clearance when loads are applied during ice-propeller interaction.
- The bearing housing should be sufficiently stiff, such that the bearing pressure is distributed to as large an area on the bossing as practical.

A number of icebreakers have incorporated these features with success, resulting in bearing life that can be as high as 10 years, including the Russian Nuclear Icebreaker “Taymyr”, the Canadian Coast Guard icebreaker “MV Terry Fox”, and Canadian Coast Guard Vessel Louis S. St. Laurent, all of which use water lubricated stern tube bearings.

EXISTING ARRANGEMENT

The existing bearing design arrangement on the USCG Polar Class vessels consists of a bearing housing with dove-tail slots in which bearing staves are inserted. Thordon XL, a synthetic polymer alloy, is currently used as the bearing staff material. The bearing housing is 3.4 m long, with a flange on the aft end and an internal retaining ring on the forward end. The aft end flange is bolted to the stern frame casting, and the internal retaining ring is bolted to the forward end of the bearing housing. There are three steps to the bearing housing. There are five lands that support the bearing housing, which are integral with the casting. The lands have an inner diameter of about



Photo 2 - Stern View of USCGC Polar Sea in Dock



Photo 3 – Wind Propeller Shaft



Photo 4 – Aft Stern tube Bearing Housing

1120 mm. Thirty two (32) No. 9 size staves are equally spaced around the bearing housing with a water groove between each staff that is 10 mm deep. Two sets of 1676 mm long staves are inserted into each slot. A gap of 13 mm is specified at both ends of the bearing staves for “expansion” of the staves. The existing Thordon bearing staves are specified to have a radial interference fit of about 0.25 mm in the dove-tail slots, and are required to be cooled in dry ice or liquid nitrogen prior to installation. Bonding of the staves to the dove-tail slots is allowed if a good fit can not be achieved. Removal of the bearing is usually done by cutting out the bearing material from the dove-tail slots, after the bearing housing is removed from the ship. Figure 3 illustrates the aft sterntube bossing arrangement. Photo 5 shows the center shaft aft sterntube bossing of the USCGC Polar Star. Photos 6 and 7 show the port shaft aft and forward sterntube bearings in their housings, respectively. The sterntube bearing particulars and mechanical properties are listed in Table 1.

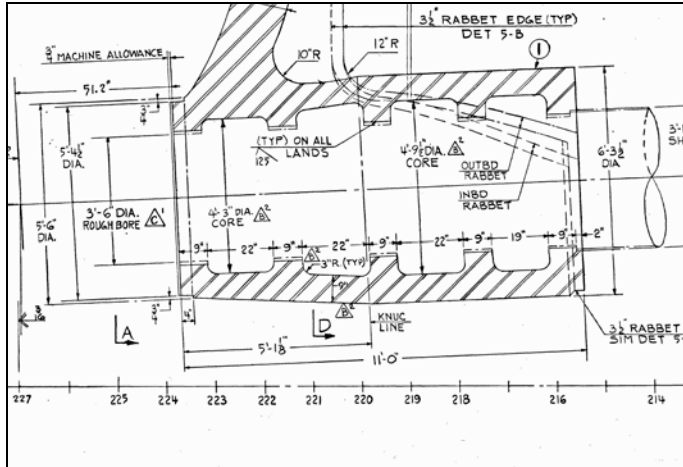


Figure 3 - Aft Sterntube Bossing Arrangement

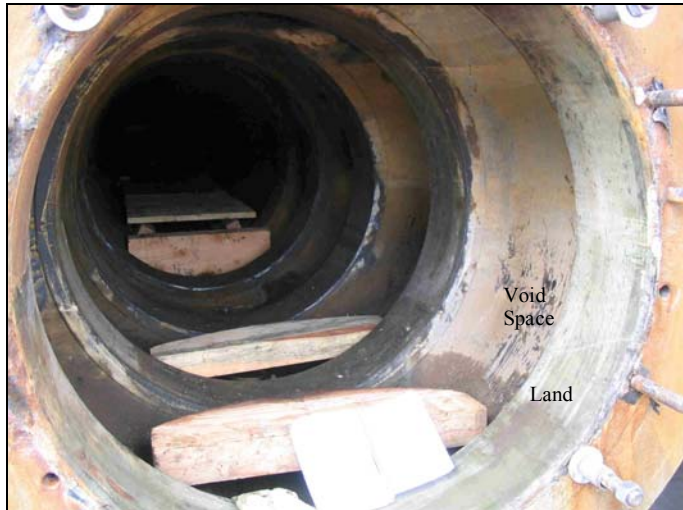


Photo 5 - Aft Sterntube Bossing – Looking Forward



Photo 6 - Aft Sterntube Bearing – Looking Aft



Photo 7 - Forward Sterntube Bearing – Looking Aft

The shafting, bossings and bearings were inspected during a visit to the USCGC Polar Star at Todd Pacific Shipyards in Seattle, Washington on June 28th and 29th. The vessel was in dry-dock and all three propeller shafts and all sterntube bearing housings were removed. The vessel had made 2 trips to the Antarctic since its last docking in 2003. It was observed that a number of staves had “migrated” longitudinally such that the ends of the staves were pushed up against the retaining rings and were damaged. Although none of the staves in the forward sterntube bearings had moved axially, it was stated that these staves had in the past also moved axially forward to the extent that they were affecting the forward sterntube bearing seal. The port aft sterntube bearing wear pattern indicated that the bearing was supporting the shaft at the aft and forward ends, and not at all in the middle.

Table 1 - Aft Sterntube Bearing Properties

Supplier	Thordon
Type	Journal
Lubrication	Water
Material	Polymer Alloy
Dimensions	
Length [L] (mm)	3353
Shaft Diameter [D] (mm)	921
Length/Diameter	3.6
Dry Diametral Clearance (mm)	3.6
Wet Diametral Clearance (mm)	3.0
Radial Water Absorption (%)	2.00%
Axial Water Absorption (%)	0.50%
Water Groove Depth (mm)	10
Allowable Relative Shaft Slope (mrad)	0.6
Mechanical Properties and Loads	
Max. Rated Load (kN)	1,850
Rate Projected Area Pressure (MPa)	0.6
Static Load (kN)	689
Static Projected Area Pressure (MPa)	32
Elastic Modulus (MPa)	490
Tensile Strength (MPa)	34
Shear Strength (MPa)	45
Impact Strength (Notch ASTM D-256-73) Nm/m	160
Poisson's Ratio	0.45
Hardness (ASTM D-2240-68) Shore D	73
Maximum Operating Temperature (Deg C)	107
Minimum Operating Temperature (Deg C)	-62

INITIAL CONCEPT

The USCG draft proposed arrangement called for the existing bearing housing to be chocked in to the bossing using a resin chocking material to provide a tight fit between bearing housing and stern tube lands. The bearing material would then be removed with the bearing housing in place. Pre-cast foam was suggested as an option to fill most of the void space between the lands. Figure 4 illustrates the proposed arrangement. This solution is elegant and solves a number of problems with the existing design; however, there are a number of features of this proposed arrangement that could be improved upon. The following sections provide analysis and recommendations regarding the proposed modification. A number of changes to this initial proposed arrangement were proposed, to better fulfill design considerations previously discussed.

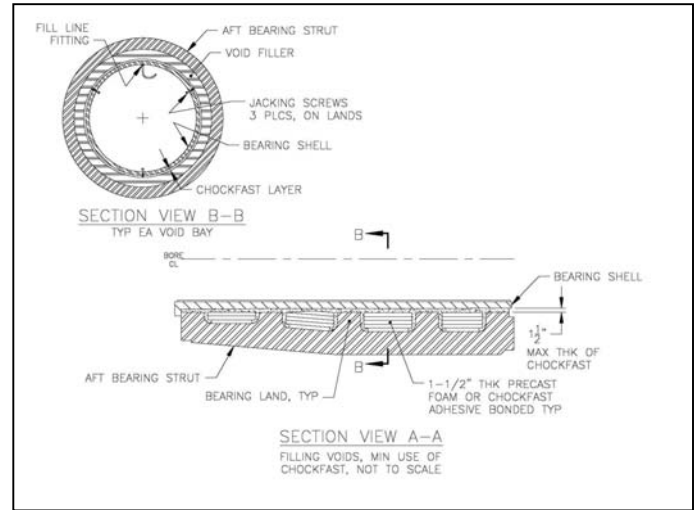


Figure 4 - Chocking Arrangement – Initial Concept

CHOCKING AND FILLER MATERIAL

Foam Filler

The option of using foam filler between the lands was considered to reduce the volume of chocking resin required. However; this filler does not provide sufficient support to the chocking resin under the bearing housing, and essentially results in a “bridge” of chocking resin across the lands. This “bridge” would likely crack under the pressure exerted during ice propeller interaction. For example, a pressure of 8.3 MPa can be expected to be applied on the span between the lands. This can result in a shear stress as high as 62 MPa, which exceeds the shear strength of a typical resin (37 MPa). Therefore, using foam filler between the lands was considered unacceptable.

Steel Rings

The option of placing steel rings between the lands to reduce the amount of resin was considered. Steel lands were welded into the forward sterntube bossing, and a similar procedure and material could be used between the lands of the aft sterntube bossing. Steel bands would provide adequate support for the Chockfast. The use of welded steel rings to restore the aft bearing lands was ruled out on previous investigations by the US Coast Guard, primarily because the bossing is an HY-80 casting. Although HY-80 castings can be welded there are requirements for preheat and post weld heat treatment. There are methods which could be used to perform this weld repair; however the shipyard stated that this was not a preferable option. Therefore, this option is not considered cost effective or practical.

Chocking Resins

Using a marine chocking resin as the only filler between the lands is the preferred option. This resin would also be used to support the bearing housing and chock it in place. Therefore, the bedding and filler material can be installed at the same time. The volume of resin required to fill all of these voids with 12 mm thickness above the lands, would be about 1.45 m³, which would require about 340 – 6.8 kg containers (2312 kg) of chocking resin. If the bearing length is reduced to 2591 mm (as proposed later in this paper) the amount required is reduced to 248 – 6.8 kg containers (1686 kg). The thickness and volume requirements will require several pours and close monitoring of the temperature, but the properties of the resin can

be maintained for such thick pours. For some resins, the first layer is poured, then allowed to set until the temperature starts dropping (about 1 hour), at which time the next layer is poured. This continues until the bearing is chocked in place. In this way the bond between the pours has the same material properties as the rest of the resin. The maximum thickness of the resin would be about 216 mm.

A number of chocking resins were considered adequate. ITW Philadelphia Resins' "Chockfast Orange" was considered the most common and tested. In addition this resin was considered adequate to withstand the shock loads and pressures due to ice-loads on the propeller. Table 2 lists the material properties for Chockfast Orange.

Table 2 Chockfast Orange Physical Properties

COEFFICIENT OF LINEAR THERMAL EXPANSION: Temperature Range 0° to 60°C	30.8 x 10 ⁻⁶ /C° (17.1 x 10 ⁻⁶ /F°)
COMPRESSIVE MODULUS OF ELASTICITY:	37482 kg/cm ² (533,000 psi)
COMPRESSIVE STRENGTH:	1336 kg/cm ² (19,000 psi)
CURE TIME:	48 hrs. 15°C 36 hrs. 18 °C
HARDNESS - BARCOL:	40-44 fully cured 35 minimum
FIRE RESISTANCE:	Self-extinguishing
IZOD IMPACT STRENGTH:	0.27 Newton m/cm 6 in.lbs./in. (greater than concrete)
LINEAR SHRINKAGE:	0.0002 mm/mm (0.0002 in/in)
SHEAR STRENGTH:	380 kg/cm ² (5,400 psi)
SHOCK RESISTANCE:	Pass MIL-S-901C (Navy) High Impact Shock Test, Grade A, Type A, Class 1
SPECIFIC GRAVITY:	1.58
TENSILE STRENGTH:	349 kg/cm ² (4,970 psi)
THERMAL SHOCK:	Pass -18°C to 100°C (0°F to 212°F)

BEARING MATERIAL AND DESIGN

More than one bearing material would be suitable for the aft sterntube bearing on the Polar Class vessels, each with its own advantages and disadvantages. A number of materials were considered adequate.

The following bearing designs were evaluated:

- (i) Navy Standard Staves in Dove Tail Slots
- (ii) Segmented (demountable) Staves
- (iii) Fully Grooved (water grooves completely around bearing)
- (iv) Partial Arc (smooth bottom bearing, water groove on top)

Bearing performance is often characterized by the following criteria:

- Wear rate
- Flexibility (pressure and allowable misalignment)
- Friction at Start-Up

- Durability in dry/low water flow conditions
- Performance against abrasion
- Low Shaft Speed Operation
- Water Absorption
- Ease of installation and removal
- Response and impact strength from ice loads on propeller

The existing bearing has thirty two (32) No. 9 size staves that are equally spaced around the bearing housing. Two sets of 1676 mm long staves are inserted into each slot. As a result of a detailed evaluation, it was recommended that the inner bore of the bearing housing be smooth so that a segmented, fully grooved or partial-arc type bearing could be installed. These bearing designs provide for a much better condition for hydrodynamic lift than the existing dove-tail slot design, since bearing surface is larger relative to the water grooves. In addition, during ice-propeller interaction more bearing surface supports the shafting resulting in better distribution of the ice loads to the bearing housing and bossing.

BEARING LENGTH

The existing bearing is 3352 mm, which corresponds to 3.6 times the shaft diameter. The static load on the aft sterntube bearing is about 690 kN resulting in a projected area pressure of 0.22 kPa (32 psi). Traditionally the length of the aft sterntube bearing was chosen to be about 4.0 times the shaft diameter, and a maximum projected area pressure of 276 kPa (40 psi). This criterion was developed empirically when aft sterntube bearings were first used to support the screw propeller shaft. At this time water lubricated aft sterntube bearings were made from lignum vitae, a very dense wood. Water grooves were incorporated to help "flush" out the dirt and contaminants from the water, so that untreated sea water could be directly pumped through the bearing. Oil lubricated white metal bearings were developed in the 1940's to replace the lignum vitae bearings. However, up until about the 1960's lignum vitae bearings were still installed on ships with water lubricated sterntube bearings, after which rubber and synthetic compounds were used. Today it is common for water lubricated aft sterntube bearings to be made from synthetic materials, and have lengths of about 2 times the shaft diameter. Ship Classification Societies allow aft sterntube synthetic bearings to be as short as 1.5 times the shaft diameter with projected area pressure of up to 0.60 MPa (87 psi).

Studies, and operational experience, have shown that aft sterntube bearings with relative lengths similar to the Polar class bearings, are loaded along less than 60% of their length [Cowper, et. al. 1988]. In fact there are occasions that the forward end of a long bearing becomes top-loaded, restricting the natural bending curve of the shaft causing higher loading on the bearing, especially on icebreakers. An inspection of the USCG Polar Star bearings during an on-site visit to the shipyard indicated that the port and starboard aft sterntube bearings were loaded at the aft and forward ends, and not in the middle – which may be an indication of a combination of misalignment and excessive bearing length. A shorter bearing length offers the following advantages:

- Less filler material required between lands
- Less bearing material
- Easier installation and removal
- Better lateral (whirling) vibration characteristics
- No top loading of forward end of the bearing.
- Easier adjustments for alignment

Two shorter bearing lengths were considered feasible: 1803 mm and 2591 mm. With a bearing length of 1803 mm, the bearing would extend to the forward end of the third land, and the projected area pressure would be 0.41 MPa (60 psi) with a length to shaft diameter ratio of 2.0. With a bearing length of 2591 mm, the bearing would extend to the forward end of the fourth land, and the projected area pressure would be 0.29 MPa (42 psi) with a length to shaft diameter ratio of 2.8. To accommodate the higher projected area pressure, the 1803 mm long bearing would require a partial-arc typed design (smooth bearing surface). The primary disadvantage of the 2591 mm long bearing is that it would be harder and more expensive to install than the 1803 mm bearing. The advantages are that a fully grooved or segmented stave type design could be used. The fully grooved and segmented stave bearings have proven success in ice-class service and are less susceptible to high wear of the shaft sleeve. After careful consideration, a bearing length of 2591 mm was chosen so that the proven fully grooved or segmented bearing design could be installed.

CONCLUSIONS AND RECOMMENDATIONS

- A segmented or fully grooved type bearing was recommended. These bearing types offer a larger surface area that supports the shafting, resulting in better distribution of the ice loads to the bearing housing and bossing. In addition, these bearing designs provide for a much better condition for hydrodynamic lift than the existing dove-tail slot design, since the bearing surface is larger relative to the water grooves.
- The results to date indicate that all bearing materials examined would be suitable for use on the USCG Polar Class Vessels. Since the existing bearing material, Thordon XL, has had acceptable performance, it was chosen for the new bearings.
- A chocking resin was chosen to be used to fill all the voids between the lands and above the lands to secure the bearing housing in place. A number of marine chocking resins would likely suffice for this application. Chockfast Orange, from Philadelphia Resins, was chosen because of its proven success on icebreakers, high impact resistance, and common use in marine aft sterntube bearings.
- The bossing is sufficiently stiff and no modifications were recommended, with the exception of preparation for the chocking resin. This included boring out the inner diameter of the lands to ensure a clearance of 37 mm between the outer bearing housing and the lands in the bossing. This clearance is required to allow for realignment and sufficient chocking resin between the lands and the bearing housing.
- The existing bearing length of 3352 mm is considered too long, resulting in poor pressure distribution across the length of the bearing. A bearing length of 2591 mm was recommended, since a fully grooved or segmented bearing design could be employed, which have proven success on icebreakers.
- The inner bore of the existing bearing housings is required to be machined to a smooth bore to accommodate the new bearing design.
- Since no work on the new bearings is expected for 8 to 10 years, a savings in repair/maintenance of about \$230,000 per bearing each year can be realized. In addition, there will be a reduced risk of an unscheduled docking due to premature bearing or seal

failures. Therefore, it is estimated that over a 20 year period, a potential savings of \$13,000,000 US can be realized by implementing the proposed modifications.

The recommended modifications to the aft sterntube bearing were implemented on the USCGC Polar Sea during dry-docking in March and April 2006 at Todd Pacific Shipyards Corporation.

ACKNOWLEDGEMENTS

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