

# Eliminating the “Achilles’ heel” of An Open Seawater Lubricated Shaft Line with a New Shaft Coating System that Prevents Corrosion and Extends the Shaft Withdrawal Period.

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## ABSTRACT

Seawater lubricated propeller shaft bearing systems have proven to be a reliable, simple and efficient pollution-free alternative to oil lubricated sealed systems, which contribute significantly to ocean pollution due to habitual seal leakages. However, the adoption of clean technologies such as Thordon COMPAC bearings have found resistance, as often a factor mentioned when discussing their attributes is the risk of shaft corrosion.

Traditional shaft corrosion protection coatings have been considered the “Achilles’ heel” to the open system technology due to their tendency to develop cracks during service operations. Existing marine epoxy systems use fiberglass tape in an attempt to produce a reliable covering. However, it is this very same element that is the weak link in this system.

In a pioneering approach among seawater lubricated bearing manufacturers, Thordon Bearings has concentrated over 15-years of Research & Development to produce a reliable solution. Thordon’s R&D Polymer Chemists have developed Thor-Coat, a toughened, modified epoxy coating *without fabric* designed to provide 10-year integrity and to potentially eliminate the need for the 5-year shaft withdrawal.

This paper presents the development program that Thordon adopted to build a flexible coating system. The document also shares lessons learned along the way of the developmental journey.

## INTRODUCTION

Open seawater lubricated stern tube bearing technology is not new to the marine industry. It dates back to the earliest days of shaft-driven propeller ships when seawater was used as a lubricant for lignum vitae bearings. Looming supply shortages of quality lignum vitae in the 1950’s, coupled with technological advances in sealing technology, led to the adoption of closed oil lubricated white metal bearings. This new standard appeared to address all marine stern tube issues as it was touted as a controlled closed system that could provide a reliable and predictable envelope for bearing performance. However, it had one major drawback; stern tube oil leakages were inevitable and accepted as normal operational consumption. Global environmental awareness has since moved the issue of acceptable oil leakage for routine operations to the forefront as a significant environmental concern with strict rules and full legal consequences.

The marine industry is justifiably returning to open seawater lubricated stern tube bearings in response to the environmental concerns associated with *sealed* oil lubricated stern tube bearing systems. The Thordon COMPAC system, which is an open seawater lubricated bearing, is the result of over two decades of advancements in the design and implementation of practices that facilitate predictable and controlled wear rates of non-metallic stern tube bearings.

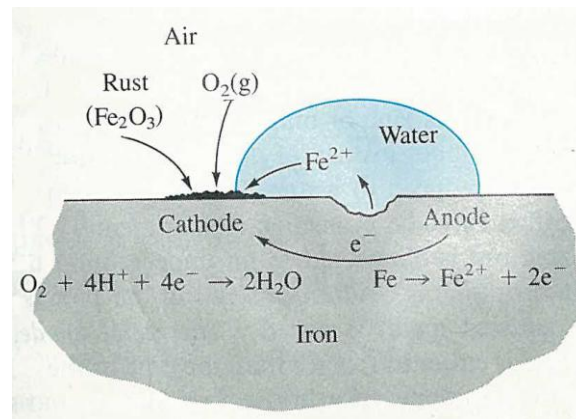
A critical design consideration in the COMPAC bearing system is the corrosion protection of the carbon steel shaft. In a pioneering approach, among seawater lubricated bearing manufacturers, Thordon Bearings has invested over 15-years of Research and Development to produce a solution. Thor-Coat Marine Shaft coating was engineered as a toughened, modified, two-part epoxy coating *without fabric*, designed to provide 10-year performance integrity and to

potentially eliminate the need for the 5-year tail shaft withdrawal associated with seawater lubricated bearing systems as required by Classification Societies.

This paper outlines the details of the development program undertaken to meet the rigorous requirements to build a flexible marine coating system with high toughness and superior anti-corrosion characteristics. Properties of coating technology and how they are applied to the protection of carbon shafts are also described. The document concludes by presenting some of the challenges faced in the development of a new marine shaft coating.

## UNDERSTANDING COATING TECHNOLOGY AS IT APPLIES TO PROPELLER SHAFT CORROSION PROTECTION

All surfaces undergo a level of degradation due to continual contact with moisture and oxidizing agents such as air. Left unprotected, steel parts exposed to harsh marine conditions will undergo *electrochemical* corrosion as a combination of conditions exist such as variations in water velocities, salinity levels, dissolved oxygen content, temperature, and pH levels (amongst others). The process of corrosion is complex and as such the finer details and chemical equations involved, although significant, are outside the scope of this paper. The basic steps involved in the corrosion process are illustrated in *Figure 1*.



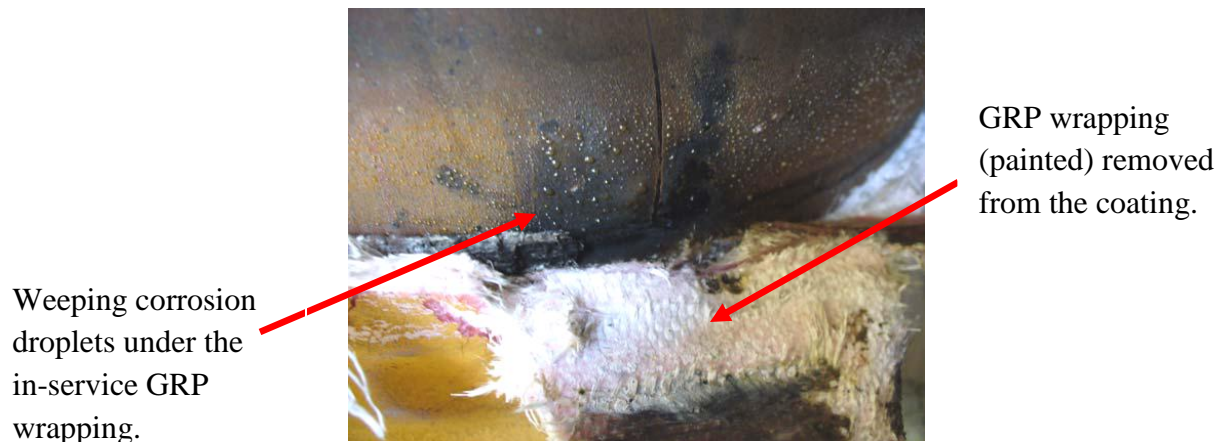
**FIGURE 1** The Basic Process of Corrosion (Gillespie et al, 1989, pg 819)

The key concept in the preceding diagram is the formation of localized and dissimilar electrochemical sites on the surface of the unprotected metal. These sites when in contact with water and air (or dissolved oxygen) will contribute to the movement of electrons from an anode location to a cathode location. In the presence of seawater, composed of salts and minerals, the rate of these reactions is accelerated.

An entire industry has been devoted to the protection of marine metal structures with the use of various corrosion protection measures including, but not limited to, organic and inorganic coatings, metallic coatings, cathodic protection, linings and laminates. In very general terms, coatings are meant to protect metals by acting as a barrier that prevents oxidizing agents (such as water or dissolved oxygen) from interacting with the surface which halts the formation of these electrochemical sites and blocks the movement of electrons within the metal.

With the exception of naval vessels and merchant vessels of very high power, mild steel is used for both inboard and outboard shafting (Long 1971, pg 372). Propulsion shaft casualties are caused principally by corrosion, fatigue and fretting corrosion. Steps are usually taken to protect the shaft from seawater corrosion by applying protective coatings or coverings (Williams & Gross 1971, pg 810). The typical anti-corrosion arrangement for shafts has been a wrapping where a polymer-based coating is combined with fiberglass tape with the intention of improving on durability and the mechanical properties of the base coating.

The fiberglass reinforced system or glass reinforced plastic (GRP) wrapping has often been considered the Achilles' heel of an open water lubricated bearing arrangement because of its inability to resist cracking caused by normal torsional and bending forces natural to the operation of the shaft. Cracks in the GRP coating let in seawater between the coating layers and the metal, creating a condition that promotes severe damage of the shaft by several modes of localized corrosion; the most predominant of which is oxygen-concentration corrosion. The oxygen-concentration cell is an electrolytic cell resulting from the difference in the oxygen concentration between two locations (Perry 1984, pg 23-3). For the GRP wrapping, when damaged, the corrosion process will be accelerated underneath the wrapping since the oxygen concentration is low and the concentration of chloride ions is high from seawater ingress. Damaged GRP wrapping has also been known to foster environments where a secondary type of corrosion known as 'weeping' corrosion is encountered. *Figure 2* shows the condition of a shaft with the GRP wrapping lifted from an in-service shaft.



**FIGURE 2** Corrosion as seen under GRP wrapping (Padgett Swann Machinery, FL, USA, March 2007)

While the GRP wrapping system provides a hard system for protecting shafts from impact damage, it suffers from low ductility and flexibility when the substrate is subjected to bending. In addition, if the surface preparation of the shaft was less than ideal, i.e. non-sandblasted, prior to the application of the GRP system, the degree of adhesion for the polymer coating is measurably reduced. Thordon Bearings' experience has been that the Classification Society Surveyors are interested in examining the integrity of the coating more than the bearing condition when they conduct 5-year withdrawal inspections. However, damage to the shaft at an area other than the point of seawater ingress can be difficult to detect.

## **THOR-COAT: THE PRODUCT DEVELOPMENT PLAN**

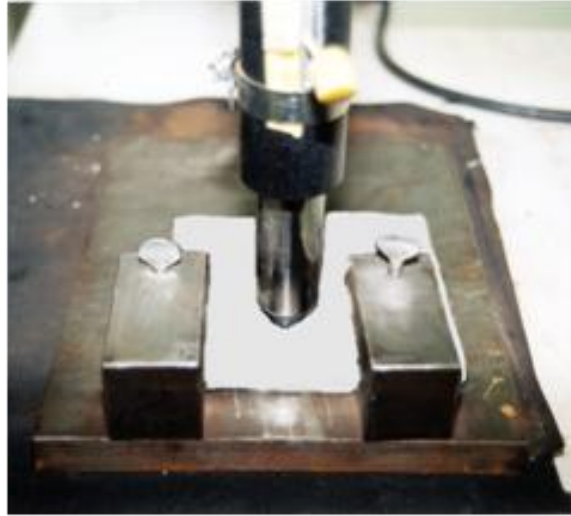
An understanding of coating technology is essential to develop a system that overcomes the shortcomings of the typical wrapping shaft coating to attain superior corrosion protection. Thor-Coat was engineered as a toughened two-component epoxy based system to meet the following criteria:

- Excellent adhesion to the substrate even after extensive periods of water immersion;
- Ability to withstand impact forces during installation and service;
- Excellent water vapour transmission resistance to provide long-term corrosion protection to metal shafts;
- Superior coating film flexibility and ductility to resist cracking due to torsion and bending stresses experienced by propeller shafts;
- Ability to apply the coating in one single application possibly reducing the dry dock times;
- Ease of application in order to minimize the high labour cost associated with GRP wrapping systems.

A Product Development Plan was established to achieve the preceding criteria for evaluation of the Thor-Coat coating system. The following sections describe the general arrangements of these tests.

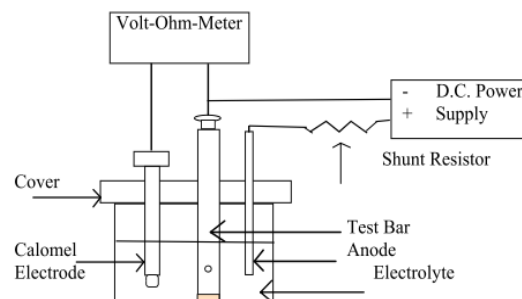
Along with superior corrosion protection, the ability to withstand impact is essential for any marine shaft protection coating. The **Falling Weight Test (FWT)** (ASTM G14) is an effective tool for assessing the ability of the coating to resist the sort of mechanical damage that can result from handling large propeller shafts during transportation or installation.

The test requires a 1-kg [2.2-lbs] weight, known as a *tup*, to be dropped from a height of 135-cm [53"] onto a carbon steel plate that is protected by the test epoxy coating (see *Figure 3*). Observations (both visual and with instruments such as a spark tester), measurements and calculations are made to determine the resistance to cracking and the relative impact strength in mm·kg [in·lb] from the drops on each coated plate. A coating passes only when it shows no signs of damage particularly from crack propagation. Typical values obtained for an impact-resistant epoxy material would be in the range of 230-mm·kg [20-in·lbs] (Guan & Kennedy 1996). Thor-Coat achieves an impact resistance rating of 1350- mm· kg [117-lb·in].



**FIGURE 3** Falling Weight Test  
(Thordon Bearings R&D Laboratory, ON, Canada, 2004)

A **Cathodic Disbondment Test** (ASTM G8) is an essential test for demonstrating the adhesive properties of a protective coating when exposed to electrical stresses particularly when voids and defects are present in the coating, or when there is an imbalance in the corrosion protection impressed current system for the vessel. Electrical flow imbalances can occur as the vessel is immersed in seawater which acts as a conductive electrolyte. The bond between the coating and the shaft must serve as a corrosion barrier if an opening in the coating were to occur. The diagram in *Figure 4* depicts a coated test bar compromised by a hole drilled in the coating while being subjected to varying electrical potentials. This test simulates, in an accelerated fashion, the effect of aggressive corrosion advancing to adjacent metal substrates when a coating has sustained direct damage while stressed. The loss of adhesion to a coating is expressed as the Equivalent Circle Diameter (ECD) with 4-mm [0.157-in] being the maximum allowable coating radial disbondment accepted in accordance to Annex A1 of ASTM A775. Under electrical duress by an electrical current, Thor-Coat exhibited an ECD result of less than 1-mm [0.04-in] and resisted break down with no corrosion or blisters observed at the conclusion of this test.



**FIGURE 4** Cathodic Disbondment Test  
(Thordon Bearings R&D Laboratory, ON, Canada, 2004)

A corrosion protection method is effective when a barrier against oxidizing agents and seawater ions is formed. The **Water Vapor Diffusion Test (WVDT)** (ASTM D1653) measures how impervious a coating is to water transmission, an important factor for marine protective coatings. Units measured in SI are called *perms*. Typically, epoxies have WVDT ratings at around 0.19 perms (Information Technology Specialists Inc. 1996). Thor-Coat has a WVDT rating of 0.043 perms.

The strength of a coating is measured by the **Lap Shear Strength Test** (ASTM D1002) and the **Film Tensile Test** (ASTM D2370). The first test evaluates the ability of a coating to adhere to the carbon steel substrate it is protecting. Long-term adhesion testing provides a fair indication of adhesion losses that occur over time. The Film Tensile test also yields key comparative analysis data for the tensile strength, the ductility and the resistance to fracture of a material when stressed. Testing of Thor-Coat under these two conditions resulted in a lap shear adhesion of 21-MPa [3050-psi] and a film tensile strength of 18-MPa [2618-psi]. An effective cured coating will possess high strength without compromising the required level of flexibility.

The **Conical Mandrel Bend Test** (ASTM D522) is a quick evaluation that shows how coatings react to severe bending on coated carbon steel test specimens. The test evaluates the resistance of a coating to cracking from typical operational stresses in locations where it is difficult to see damage. *Figure 5* displays a coated substrate bent around an extremely small radius to simulate severe bending and torsional stresses on a marine propeller shaft. Thor-Coat resisted cracking when exposed to an elongation of 160%.



**FIGURE 5** Conical Mandrel Bend Test  
(Thordon Bearings R&D Laboratory, ON, Canada, 2004)

The **Wet Abrasion Test** (ASTM G6) is an accelerated wear test that exposes a coated carbon steel sample (*Figure 6*) to a rotating slurry mix of coarse abrasives and water as would be experienced by a vessel operating in harsh environments such as a silt-laden shallow river. Under wet conditions, using in-house testing per ASTM G6 parameters, the loss of thickness for typical marine shaft coating systems was in the range of 3-15%. Thor-Coat exhibited a loss of thickness less than 1%.

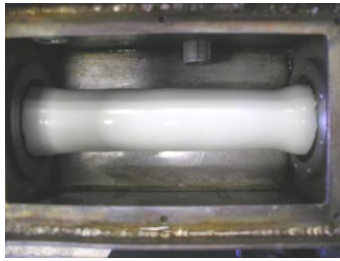


**FIGURE 6** Wet Abrasion Test  
(Thordon Bearings R&D Laboratory, ON, Canada, 2004)

Testing in the laboratory to replicate real application parameters can be challenging. The **Four-Point Bend Test** comes closest to achieving the ultimate goal of bringing the outside world conditions into the laboratory. This test measures the resistance of Thor-Coat Marine Shaft Coating to crack formation and gauges fatigue from stresses inherent to marine propeller shafts.

Initial testing was conducted by adapting a traditional four-point bend test (ASTM E855 Method C) and by following design parameters as presented by the Materials Department of Lloyd's Register House (1998) to simulate bending of a marine propeller shaft in-service. Following Lloyd's Register guidelines, a 50-mm shaft diameter with a 1-mm protective coating was tested under a cyclic load. A test was considered a PASS when the Thor-Coat showed no evidence of cracking or loss of adhesion on completion of 1-million cycles with inspection each 100,000 cycles.

Refinements to the test plan began in 2005 (*Figure 7*) to incorporate the testing of various thickness of coatings to be tested at stress levels of 200% (typical principal maximum stresses encountered by vessels calculated at 51-MPa). This testing was done for extended periods (10-million cycles or greater) under conditions that more closely mimic inhospitable marine service conditions.



Circulating saltwater immersion bath showing Thor-Coated test section of shaft



**FIGURE 7** Four-Point Bend Test  
(Thordon Bearings R&D Laboratory, ON, Canada, 2008)

The results of the test program as they relate to the Thor-Coat Marine Shaft coating have been described in the preceding sections. *Table 1* summarizes the data from this Product Development Program.

**TABLE 1** Summary of Thor-Coat Test Data

Test	Method	Results
Impact Resistance - Falling Weight	ASTM G14	1350-kg·mm [117 lb-in.] for a thickness of 2-mm [0.08"].
Cathodic Disbondment	ASTM G8	<1-mm [0.04"] ECD<4-mm [0.2"] No blisters or corrosion.
Water Vapor Diffusion	ASTM D1653	0.0028 metric perms [0.0043 perms].
Lap Shear Adhesion	ASTM D1002	21-MPa [3050 psi]
Film Tensile	ASTM D638	18-MPa [2618 psi]
Conical Mandrel	ASTM D522	Calculated at 160% elongation at 180° for a thickness of 2-mm [0.08"] & no cracking at 180° full bend.
Wet Abrasion	ASTM G6	0.015-mm [0.0006"] for a thickness of 1.7-mm [0.07"] or 0.60 g [0.021 oz.] by weight. Note: Test conducted at 2x speed and duration.
<small>Report #1344 by JF &amp; LB; Dec.2004</small>		
Four-Point Bend	in-house	Passed 200% load @ 100-MPa for 10 <sup>6</sup> cycles

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## OVERCOMING THE CHALLENGES DURING THE DEVELOPMENT OF A NEW MARINE SHAFT COATING.

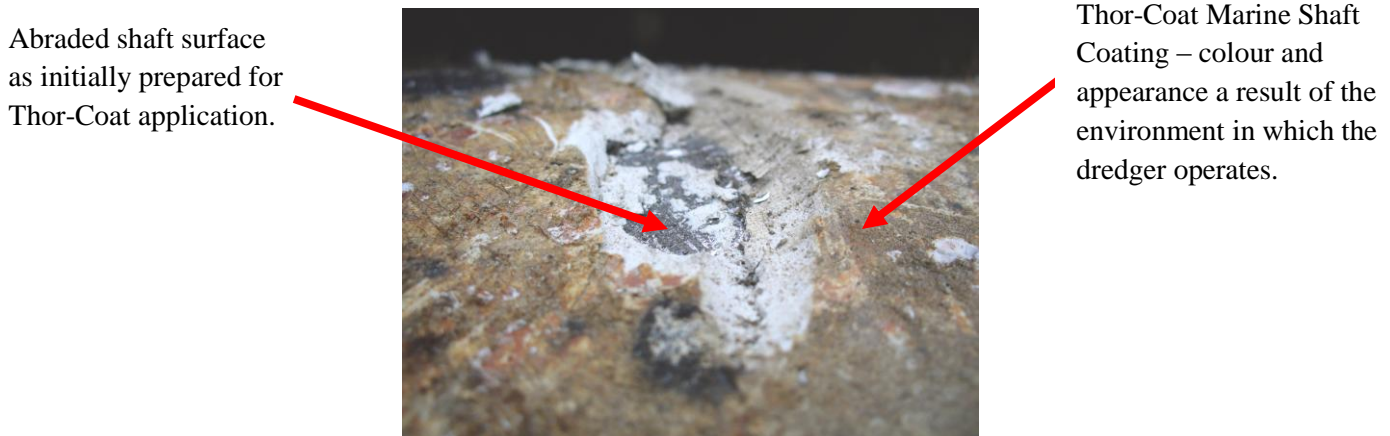
### *Dependency on Material Suppliers*

The introduction of any new product into the market is done only when extensive validation testing has been completed. Developmental testing is intended to scientifically demonstrate that the product is ready to meet the routine demands of service and any other challenges it may encounter. After completing an exhaustive series of tests, the first generation of the Thor-Coat Marine Shaft Coating was tested in field applications in early 2001. The first set of field trials yielded a rather irregular and alarming result – a loss of coating adhesion and a hardening of the coating that resulted in a loss of flexibility with time.

Thorough evaluation of the coating production process revealed that a base component, formulated and supplied by an outside source, had been altered causing a significant variation in the physical properties of the final cured product. This modification had a major impact in the adhesion for the cured coating when exposed to seawater over a significant time period. An exhaustive pre-testing program and standard quality control property verification testing had proved insufficient for detecting formulation changes as made by the supplier.

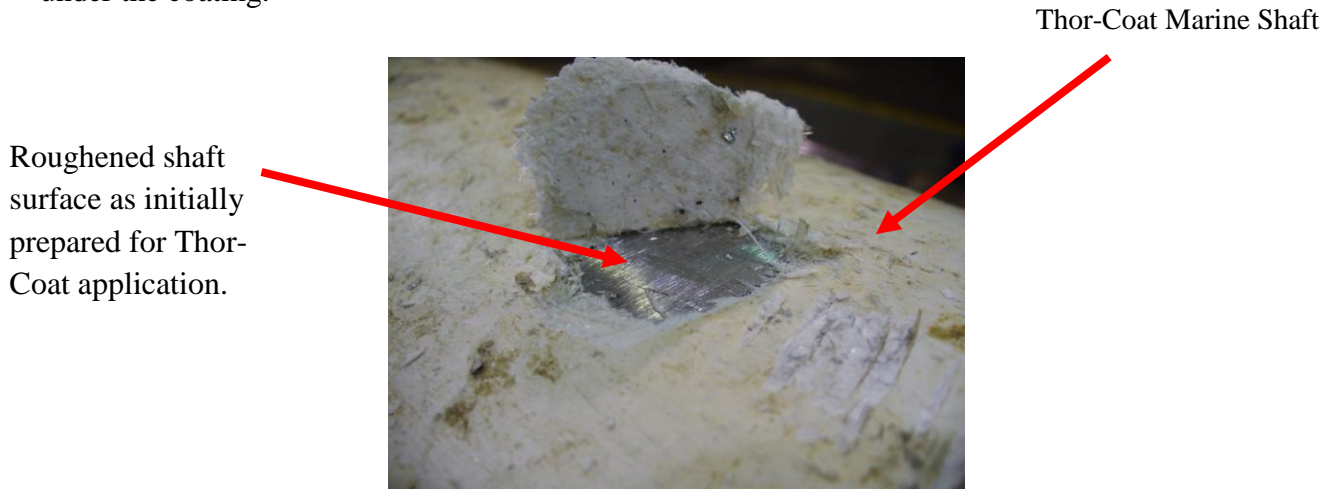
The discovery dictated that the Thordon R&D Group react swiftly to remedy the situation. It accomplished this by self-formulating in-house the components of the coating thus gaining complete control of the formulation process and quality measures. By October 2003, another round of evaluation testing had been completed and the second generation of the Thor-Coat Marine Shaft Coating was available for field testing.

The first test for Thor-Coat was on the shaft of the dredger *Tom James*, owned by Weeks Marine in Louisiana, USA, and operating in the Gulf of Mexico. In March 2007, the first inspection of the coated dredger shaft took place. The coating remained intact after three-years in service; requiring the examiner to intentionally break the coating to assess the metal underneath it. No evidence of corrosion was found as seen in *Figure 8*.



**FIGURE 8** – Inspection site showing Thor-Coat condition after 3-years of service.  
(Thordon Bearings Field Services, LA, USA, 2007)

A second field application became available for evaluation with the coating of a tail shaft for a towing vessel, the *Arctic Dawn* (owned by Dawn Offshore Towing, Louisiana USA) and first coated in December of 2004. This vessel operated for two-years in the Gulf of Mexico. Inspection of the coating revealed that the shaft retained its original state with no evidence of corrosion observed under the protective Thor-Coat Marine Shaft Coating. The machine shop, working on repairs to this shaft, indicated the coating had adhered extremely well to the metal – so well they had to machine it off to gain access to an area where the shaft had cracked (the result of poor design in shaft sizing). *Figure 9* presents a close-up view of the metal surface under the coating.



**FIGURE 9** – Inspection site showing the fishing vessel shaft after 2-years of service.  
(Thordon Bearings Field Services, LA, USA, 2007)

Close monitoring of coated shafts in-service continues as part of Thordon’s Product Development Process. Monitoring of shafts in-service also serves a secondary purpose allowing bearing manufacturers to meet the strict requirements for product type approval as set out by Classification Societies. The problems that occurred with adhesion as detected with the first generation of Thor-Coat have been resolved and the field performance of the coating continues to be in-line with laboratory experience.

#### *Meeting everyone’s needs with one product*

One method to ensure customer satisfaction is to provide verifiable evidence that the product can do what it claims to do. In this instance, Thor-Coat Marine Shaft Coating must protect a propeller shaft from all foreseeable and some not-so-foreseeable perils. There are also many unforeseen expectations on the coating however even before it goes into service.

From a practical point of view, large expenditures of time, manpower and equipment are not acceptable by shipyards when considering shaft preparation to accept a shaft corrosion protection system. Preparation of the metal surface is a critical design issue and no coating is exempted. The coating must be applied to surfaces that are clean and free from contaminants with excellent surface preparation such as that obtained by means of abrasive cleaning procedures. Where

Thor-Coat differs from other corrosion protection systems is on its ease of application without compromising the performance of the cured coating. Unlike the GRP wrapping systems which is quite labour intensive (4 layers or more of fiberglass tape to be rolled around the shaft); the 2-part Thor-Coat coating is applied in one single layer at 2-mm [0.080”] minimum thickness and it can be applied by a two-person team.

Coating manufacturers will often offer different grades of materials to accommodate different climates. Thordon engineering and field representatives have found ways to overcome the need of more than one product for more than one environment. For instance, temperature control is often an issue with coating systems. In cold temperatures, the coating will take too long to cure; in hot environments, the pot life is decreased. In both cases, the manufacturer has proven that with a bit of ingenuity one coating grade can meet the demands of all customers. In winter months, in cold environments such as Northern Canada, the use of heat lamps provides the temperature control required to ensure proper coating cure. In extremely hot areas like Dubai, the use of ice can extend the pot life of the mixed components and thus the temperature can be controlled sufficiently to provide adequate time for a coating application.

An ability to overcome application impediments like extreme temperatures is not based on theoretical or scientific knowledge. However, good problem-solving aligned with a thorough understanding of the limitations of the coating help to ensure the coating is applied with good results. Knowing the product in all its stages is essential as poor coating performance is more often than not the result of poor application procedures.

## **GOING BEYOND BEST PRACTICE: OBTAINING CLASS SOCIETY APPROVALS**

Adhering to a Development Test Plan that produces accurate product specifications as dictated by ASTM industry standards lends much credence to the stated quality of a product. The Four-Point Bend Test, as referenced in the coating evaluation section, went beyond the norm for verifying the performance of a marine protective coating.

Classification societies publish rules to set standards that ensure marine vessels and their equipment are built physically and environmentally safe and remain so regardless of hazards. Severe damage caused by marine corrosion on structural components and tanks has in recent years focused the attention of Classification Societies and other organizations on the application of protective marine coatings. Classification Societies such as Registro Italiano Navale (RINA UK Ltd.) and Lloyd’s Register EMEA have become corporate members of NACE International, formerly known as the National Association of Corrosion Engineers, and are subsequently recruiting more coating inspectors to their organizations [*The Maritime Executive Magazine: RINA Expands its Coatings Expertise, July 24th, 2008*]. The attainment for approval of coatings has evolved in a similar manner as rules and standards reflect the increasing expertise being focused on the subject of marine protective coatings.

In June of 2004 approval was requested and subsequently obtained in May of 2007, for a two-part epoxy coating produced by Thordon Bearings Inc. from Lloyd’s Register of Shipping, American Bureau of Shipping, Bureau Veritas, Germanischer Lloyd and the Russian Maritime Register of Shipping. Case-by-case approval has also been obtained from Registro Italiano Navale and Det Norske Veritas.

On April 15<sup>th</sup>, 2005 a request for provisional approval of the coating was made to Nippon Kaiji Kyokai, also known as Class NK or simply NK. Precisely three-years later on April 15<sup>th</sup>, 2008 Full NK Approval was obtained. This three-year approval process emphatically underlines the rigorous requirements required to market a flexible coating system without fabric that provides high toughness and superior anti-corrosion characteristics. As alluded to previously, documents were submitted for approval which included all test plans, procedures and results, product specifications, instructions and training manuals, quality control procedures, etc. These documents were once again assembled for ClassNK review with additional information requested from NK on an in-house 4-point test rig designed from parameters set by LR to simulate typical shaft conditions on a coated marine shaft. The rig described in *Figure 7* was built following a few not so successful attempts made to conduct external laboratory bend testing on rotating shafts. These externally commissioned tests proved laborious and inadequate for proving a marine application as did industry standard tests. As frequently happens in the marine sector, the test plan and the equipment were modified to better simulate marine service conditions.

The rig evolved from a simple, static 4-point bend dry test on a carbon steel shaft (1996) to a carbon steel shaft rotating at 180 RPM in a temperature regulated, saltwater immersed circulating system (2005). Initially it was designed to complete 10,000 cycles at a load of 48 to 69-MPa [7,000 to 10,0000 psi], but by January 2008 it had run a few marathons of 10-million cycles or more with stresses of 100-MPa [14,503 psi]. Note that 51-MPa [7,396-psi] calculated in accordance with class rules, is considered the maximum principal stress typically encountered by marine shafts in service conditions. Thus, applied loads were, by design, 200% or greater to emulate the maximum principal bending and torsional stresses potentially encountered by a vessel propeller shaft in-service. The test program confirmed suitability of Thor-Coat for marine use. The strength of the results provided the impetus that turned the initial new product request for Class NK approval with one difference – the request for Provisional Product Approval was received as a Full Product Approval.

## CONCLUSION

The future for achieving pollution-free stern tube bearing systems lies with implementing seawater lubricated bearing systems into global commercial marine fleets. Extensive Research & Development investments have been made in developing the Thor-Coat Marine Shaft Coating.

The unreliable performance of traditional shaft corrosion coating protection systems or glass reinforced plastic (GRP) wrapping systems has repeatedly been an issue for open seawater lubricated systems due to the tendency for these coatings to develop cracks as a result of the torsional and bending stresses produced by normal shaft operation. Thor-Coat Marine Shaft coating possesses the flexibility and toughness to resist such stresses during operation. The *Achilles' heel* of an open water system has indeed been eliminated with the provision of superior corrosion protection for marine propeller shafts. This achievement from a *wear* point of view means that the bearing arrangement, in its entirety, has the potential of lasting the life of the vessel.

## **ACKNOWLEDGEMENTS**

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