# DGO-1: A Metal Coating/Surface Treatment Resistant to Cathodic Delamination

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*Abstract* — **Finding coatings/surface treatments that are resistant to cathodic delamination is not an easy task. Both the materials used and the inter-material bonds must be able to survive exposure to a very high pH (13-14) environment. During the last two years, the U.S. Navy has been testing non-conductive ceramic (NCC) coatings and a proprietary polymeric coating made by Teledyne/D.G. O'Brien called "DGO-1" for resistance to cathodic delamination. These experiments utilized an elevated temperature accelerated life test (ALT) in which solid, cylindrical monel 400 alloy samples were placed in a 66°C salt solution (3.5% sodium chloride) with zinc sacrificial anodes attached to simulate cable connectors subjected to an environment conducive to cathodic delamination. The DGO-1 coated samples were overmolded with PR-420 primer and PR-1547 polyurethane (PRC-DeSoto). The Arrhenius time-temperature correlation for this ALT was based upon the rate of cathodic delamination observed on bare metal monel 400 flat coupon samples made with the same primer and polyurethane encapsulant. One equivalent year (EY) of exposure was calculated to be 31.2 days in the ALT tank. Circumferential peel test data from the DGO-1 coated samples indicate that cable connectors of similar dimensions could be expected to last for 18 EYs under environmental conditions that promote cathodic delamination. DGO-1 coated samples lasted much longer than bare-metal samples made with PR-420 primer and PR-1547 polyurethane, and they also survived significantly longer than monel 400 samples with NCC coatings and standard seal coats overmolded with the same primer and polyurethane encapsulant.**

***Keywords—cathodic delamination, cathodic disbondment, cable connectors, NCC, non-conductive ceramic coatings, DGO-1; accelerated life testing, adhesion, peel testing***

## I. INTRODUCTION

To prevent corrosion damage to ship hulls or any other susceptible metal hardware submerged in seawater, some form of cathodic protection (either sacrificial anodes or an induced current cathodic protection – ICCP - system) is typically employed. An unfortunate side-effect of the use of these systems is the destruction of metal to polymer bonds via a process referred to as "cathodic delamination" or "cathodic disbondment." Hardware not directly connected to the cathodic protection system itself can become cathodically polarized when attached to a protected hull. Cathodic delamination is believed to cause hundreds of millions of dollars of damage to marine hardware every year. It is a common reason for the failure for outboard cable connectors.

Cathodic delamination is known to cause materials such as paint and polymeric encapsulants to debond from cathodically polarized metal surfaces. The process was recognized back in the 1920s [1] as a reason why paint debonded from steel. The most important chemical reaction during the cathodic disbondment of a polymer from a cathodically polarized metal substrate is the reduction of dissolved oxygen in water to generate hydroxyl anions [2, 3]:

$$2H_2O + O_2 + 4e^- \rightarrow 4(OH^-) \qquad (1)$$

The reduction of oxygen is the major cathodic reaction that occurs when the cathodic polarization of the metal substrate is below -1000 mV versus the saturated Calomel electrode (SCE). The electrons in the reaction are generated at sacrificial anodes or at an ICCP system anode. The hydroxyl ions are generated on the cathodically polarized metal surface where they create an extremely alkaline/high pH environment that weakens and degrades most metal-to-polymer bonds, eventually causing their failure.

A possible means for the prevention of cathodic disbondment would be to bond the polymeric coating/encapsulant to a non-electrically conductive surface. Non-electrically conductive surfaces cannot support equation (1) because they prevent the electrons required by the reaction from reaching the region where the polymer is bonded to the substrate. Of course, the non-electrically conductive surface itself would need to be firmly attached to any underlying metal substrate. One of the first non-conductive coatings to be commercialized was developed by TRI-Austin and called "Bond-Coat" (but became better known by its generic name, "non-conductive ceramic coating" or just "NCC coating"). Bond-Coat consists of a thin layer of metal sprayed onto the metal substrate, followed by an aluminum oxide/titanium oxide layer (about 200 microns thick) over which is applied a seal coat (typically a phenolic resin) to seal the inherent porosity in the ceramic layer. A primer and polymeric encapsulant is then applied over the seal-coat covered ceramic.

During the last five years, some cathodic delamination-induced failures of NCC-coated outboard cable connectors have been documented [4]. These failures appeared to be related to destruction of the phenolic resin-based seal coat applied over the NCC because of the high pH conditions generated by the cathodic delamination reaction (equation 1). A search was initiated for other coatings that could be applied to outboard cable connectors to prevent them from debonding even under the harshest cathodic delamination environments.

One material that was suggested for further study was a proprietary coating called "DGO-1" produced by Teledyne/D.G.O'Brien. This non-ceramic-based material has been in use for years to bond a variety of polymers to metal substrates. The exact formulation and application procedure for DGO-1 are considered to be trade secrets and are not made available to customers who chose to have their hardware coated with the material. Despite the fact that the coating is a "black box" as far as its composition is concerned, its long history of successful use in the marine environment placed it high on the list of materials to be tested for long-term resistance to cathodic delamination.

## II. Experimental Set-Up

### *A. Materials and Samples*

All of the samples used during this investigation were made using PR-420 primer and PR-1547 polyurethane purchased from PPG Aerospace/PRC-DeSoto International Corporation. The PR-1547 polyurethane was purchased as the "pre-mixed and frozen" product directly from the manufacturer. Upon receipt at NUWC Division Newport, the pre-mixed and frozen PR-1547 polyurethane was kept in a -40°C freezer. When needed to make samples, individual tubes of the frozen material were placed in a bucket of warm water for 25 minutes. During that time, the PR-1547 polyurethane thawed and reached a viscosity low enough that it could be pushed out of its plastic tube and into a metal mold. The PR-1547 polyurethane used to make samples was oven cured at 80°C for 16 hours. The PR-420 primer was mixed according to the directions provided by its manufacturer (after the part B can had been thoroughly stirred and agitated). The mixed primer was applied to either an aluminum oxide grit-blasted and acetone cleaned bare metal surface, or to DGO-1 surfaces cleaned using methyl ethyl ketone (MEK), or to NCC/SealPlus-coated surfaces cleaned using isopropyl alcohol (IPA).

The preliminary testing of the DGO-1 coating was carried out using rectangular, "flat-bar" samples made using one inch (2.5 cm) wide and four inch (10 cm) long pieces of monel 400 alloy that were 0.25 inches (6 mm) thick (figure 1). Only the middle portion of the metal coupon was primed and bonded to the polyurethane overmold. The polyurethane overmold was one inch (2.5 cm) wide, six inches (15 cm) long and 0.25 inches (6 mm) thick and overhung the end of the metal coupon by two inches (5 cm). Aluminum molds were designed and built that could make nine samples per batch. Once the polyurethane had cured, a band-saw was used to cut the samples apart. The edges of the samples were hand-trimmed with a razor blade and sanded until no polyurethane extended over the sides of the metal coupons. For those samples that would be exposed to cathodic debonding conditions, a small (10/32) threaded hole was drilled and tapped into (but not through) the bottom of the metal coupon so that a zinc sacrificial anode could be attached by means of a small glass-filled nylon screw (figure 2). The sacrificial anodes were standard, Martyr CMR-1 "boat rudder zinc" anodes (figure 2). The polyurethane tails of the samples were rounded and a small hole was drilled through the polyurethane to allow the samples to be suspended by means of a metal dowel attached to a custom designed and built plastic rack (figure 3).

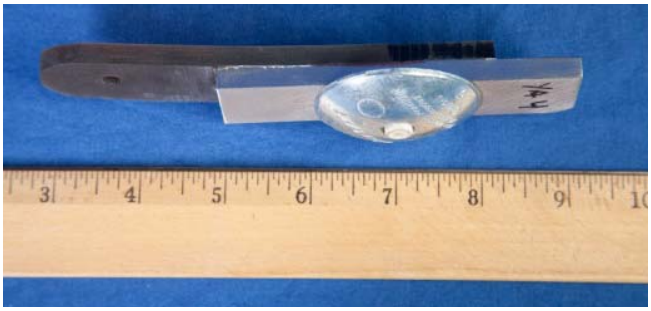

**Fig. 1.** Peel sample ready for testing. This sample has a sacrificial zinc anode attached to its backside. Only the center two square inches of the sample are bonded together.

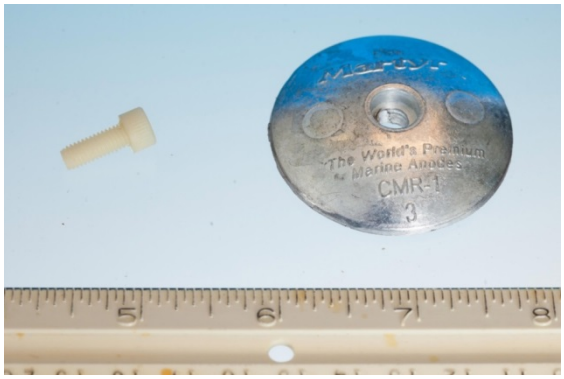


**Fig. 2.** Sacrificial zinc anode and glass-filled nylon 10/32 threaded screw.

Cylindrical, "round-stock" samples were made using solid monel 400 alloy cylinders 3.38 inches (8.58 cm) tall and 1.32 inches (3.35 cm) in diameter (figure 4). A small, threaded (10/32) hole was drilled into one of the circular faces of the cylinder so that a small sacrificial zinc anode could be attached at that location. These samples were designed to simulate connector backshells and were encapsulated with polyurethane for their entire length except for the last 0.25 of an inch (6.4 cm) of the "top" of the cylinder (the end with the threaded hole) where a sacrificial zinc anode would later be attached. Leaving some of the length of the sample uncovered by polyurethane simulated the bare metal that is typically

located between the end of the polyurethane overmold and the face of the connector (normally, a connector nut would occupy this space to allow the connector to be screwed into place).

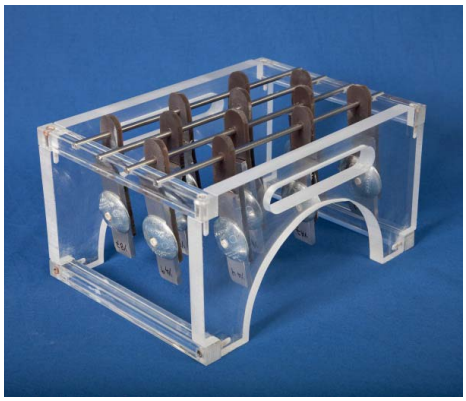

**Fig. 3.** A set of twelve individual peel samples hung by their tails from metal rods fitted into slots on top of the acrylic holder-racks, before immersion in a salt water test tank.

**Fig. 4**. Uncoated and coated cylindrical "round-stock" samples. Note that the coated sample is uniformly overmolded with a 0.25 inch (6.4 cm) thick layer of polyurethane except for the last 0.25 inches (6.4 cm) of the top end of the cylinder.

The cylindrical samples were molded in custom-designed aluminum molds that ensured a uniformly thick layer of polyurethane encapsulated the sample (figure 5). A polytetrafluoroethylene (PTFE)-based product, MS-122AD aerosol mold release (Miller-Stephenson Chemical Company), was used to prevent polyurethane from sticking to the mold. In practice, it was difficult to "stop" the polyurethane molding to leave exactly 0.25 inches (6.4 cm) at the top of the cylindrical substrate exposed as bare metal. To get around this problem, the last 0.25 inches (6.4 cm) of each cylinder was wrapped with masking tape (to prevent polyurethane from bonding) and the polyurethane was allowed to partially cover this area. The samples were then taken to the NUWC Division Newport Machine Shop, where they were mounted on a lathe and any polyurethane extending over the last 0.25 inches (6.4 cm) of the cylinder was cut away. The end result was a sample that looked like the one in the right hand portion of figure 4.

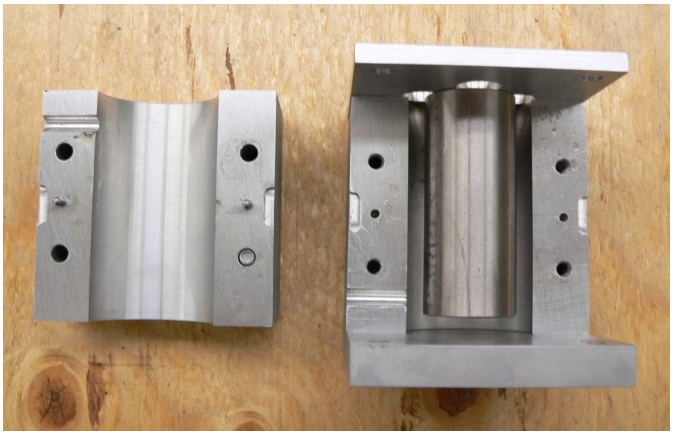

**Fig 5**. Custom-made mold for overmolding the cylindrical samples. Note that one of the cylindrical substrates is mounted in the right half of the mold; it is attached to the top of the mold via the threaded hole (which will be used to attach the sacrificial zinc anode on the finished sample). Polyurethane is pushed into the mold via the small accessway near the bottom (the left half of the mold is actually upside-down). The mold enables the precise encapsulation of the cylindrical substrates with 0.25 of an inch (6.4 cm) of polyurethane (including the bottom of the sample).

The same kind of sacrificial zinc anode used with the "flat-bar" samples was also attached to finished cylindrical samples that were to be exposed to cathodic delamination conditions in an ALT (figure 2). The zinc anode was in direct contact with the bare-metal portion of the top of the sample, and it was attached via a glass-filled nylon screw (figures 2 and 6). Because cathodic delamination was known to proceed from exposed edges inward (i.e., under the polyurethane), the cylindrical samples were designed to fail like a real connector (cathodic delamination proceeding from the exposed metal edge downwards, with the polyurethane-coated bottom of the samples being the last location to debond).

**Fig. 6**. Completely molded cylindrical samples with sacrificial zinc anodes attached. These samples are ready to be placed into the ALT tank.

Before the cylindrical samples could be peel tested, they needed to be machined. After removal from the ALT tank, each sample was rinsed in fresh water and scrubbed clean of any deposits and zinc anode decomposition products. The samples were then sent to the NUWC Division Newport Machine Shop they were first given two circumferential cuts down to the DGO-1 coating (figure 7). These cuts were necessary to allow the samples to be peeled circumferentially. Initially, it was intended that there would be three 1.0 inch (2.54 cm) wide circumferential peel strips per sample, but because of a miscalculation in the size of the cylindrical substrates, the third (bottom-most) peel strip was only 0.75 inches (1.9 cm) wide. The bottom 0.25 inches (6.4 cm) of polyurethane was also removed by the Machine Shop so that it would not interfere with the peeling of the bottom-most circumferential peel strip. Lastly, a 1.0 inch (2.54 cm) wide cut was made length-wise along the side of the cylindrical samples, removing all of the polyurethane down to the DGO-1 coating (or to bare metal if no such coating was present). This cut allowed a technician to undercut the polyurethane material of each peel strip for approximately one inch (2.54 cm) in one direction so that the grip of the Instron machine could "grab" the so-generated polyurethane tab and therewith begin the peel test. A special fixture was used to mount and hold the samples onto the Instron machine during the peel test. The fixture allowed the sample to freely rotate during the peel test, thereby ensuring that the peel tab was always at a 90° angle to the surface of the cylindrical substrate during the peel test.

**Fig. 7**. Preparation of a cylindrical sample for peel testing. First row, left to right: the zinc anode is removed and the sample is cleaned prior to machining; two parallel cuts are made through the polyurethane to the DGO-1 layer. Second row, left to right: a 1.0 inch (2.54 cm) wide cut is made down the side of the cylinder, removing the polyurethane down to the DGO-1 layer; and the bottom 0.25 inch (6.4 cm) portion of the polyurethane layer is removed.

*B. Accelerated Life Test (ALT) Procedure and Set-up*

The electrolyte solution used for the ALTs described in this report was a 3.5% by weight sodium chloride (NaCl) solution in distilled water. The use of this solution in place of real or artificial seawater simplified the resulting chemical environment surrounding the samples during the ALT, while maintaining a similar chlorinity, ionic strength and specific gravity to actual seawater. During the ALT, pure oxygen gas was bubbled into the test tank water for 15 minutes every other day to maintain the concentration of dissolved oxygen in the water. The combination of a 3.5% NaCl solution and the bubbling of pure oxygen into the water prevented the formation of carbonate anions in the ALT tank water. If present, carbonate anions would have precipitated out on, and coated, all exposed, cathodically polarized metal surfaces. The development of carbonate coatings on the metal surfaces was undesirable, because the formation of such coatings could slow or inhibit the reduction of oxygen reaction (equation 1) that generates the hydroxyl ions responsible for cathodic delamination.

Once completed, the samples were placed into an ALT tank that contained a 3.5% (by weight) solution of sodium chloride in distilled water. The tanks used were made from polycarbonate and were 18 inches (45.7 cm) by 26 inches (66.0 cm) by 15 inches (38.1 cm) in size. These tanks came with properly sized lids which were used to minimize water loss through evaporation during the length of the ALT. The water temperature was maintained at 151˚F (66°C). Flat bar samples were mounted in racks (figure 3) while the cylindrical samples were free-standing/sitting on the bottom of the polycarbonate tank (figure 8).

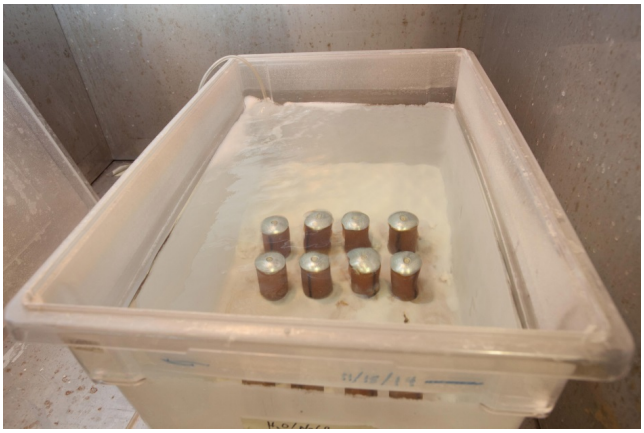

**Fig. 8**. The ALT tank being bubbled with oxygen gas (back left corner). Eight cylindrical samples are in the tank.

The choice of an activation energy for the ALT proved to be an almost intractable problem. In an earlier paper [5], a method was described by which the activation energy for a particular metal/primer/polyurethane system undergoing cathodic delamination could be calculated using the rate at which the width of the debonded region on a flat-bar sample increased over time. Unfortunately, that method for

calculating the Arrhenius activation energy (E) could not be applied to the DGO-1 coating because that coating (and the materials bonded to it) showed little or no signs of debonding or otherwise degrading during the time they spent submerged in the ALT tank. Arrhenius kinetics assume that "something" changes in the sample as a function of temperature, but the DGO-1 coating did not cooperate!

Because the actual value of E for the failure of DGO-1 coatings under cathodic delamination conditions was not known and could not be calculated using standard procedures, the Arrhenius activation energy for cathodic delamination of PR-420 primer and PR-1547 polyurethane from bare metal monel 400 alloy (8.4 kcals/mole) was used. The method by which this activation energy was experimentally determined has been described elsewhere [5] and will not be repeated here. The use of this activation energy was judged to be reasonable because it would allow the behavior of the DGO-1 coated samples in the ALT to be compared to the behavior of outboard cable connectors made using bare metal monel alloy and PR-420 primer/PR-1547 polyurethane in the field (where they last less than than six years in service under cathodic delamination conditions).

For the purposes of calculating an acceleration factor for the ALT carried out on DGO-1 coated samples, the operational temperature for the connectors when in Fleet service was assumed to be 50°F (283 K). Using 66°C (339 K) for the ALT temperature generated a RAF of 11.7, which implies 31.2 days of real time in the ALT were equivalent to 1.0 years of time in Fleet service (i.e., one equivalent year, or "EY"). The flat bar samples were removed from the ALT on a weekly basis, while one cylindrical sample was removed from the ALT tank every 31.2 days (i.e., after each EY). This same acceleration factor was used for a monel/NCC/SealPlus/PR-420/PR-1547 ALT and the small subset of bare metal monel 400 flat bar samples made with PR-420/PR-1547.

## III. EXPERIMENTAL RESULTS

### *A. Flat Bar Samples*

The initial accelerated testing of the DGO-1 coating under cathodic delamination conditions began with nine of the small, 4 inch (10.2 cm) by 1 inch (2.5 cm) rectangular coupons. These coupons had been overmolded with PR-420 primer and PR-1547 polyurethane. Three of these samples were peel tested on the Instron machine soon after they were made (i.e., these specimens were not exposed to ALT conditions). Three of the remaining samples spent one week in the ALT test tank under cathodic delamination conditions; the remaining three samples spent two weeks in the ALT tank under such conditions.

The coupons that were never exposed to salt water or cathodic delamination conditions all failed in the same manner when peel tested on the Instron machine. The failure mode was 100% adhesive between the PR-420 primer and the PR-1547 polyurethane. The average peel strength was 69.9 pli ± 2.4 pli.

Peel testing of DGO-1 coated metal coupons that had been exposed to salt water and cathodic delamination conditions during the ALT produced different results. For these samples, the polyurethane substrate eventually failed cohesively after some mixed failure modes were initially exhibited. In all cases (after 1-2 weeks in the 66°C (151°F) ALT under cathodic delamination conditions) some degree of adhesive failure between the DGO-1 coating and the monel 400 alloy was observed. This particular kind of failure tended to follow the classic "window-frame" pattern of failure seen on all other samples subjected to cathodic delamination conditions. In five out of the six samples, some degree of adhesive failure between the PR-420 primer and the PR-1547 polyurethane was also observed. Figure 9 is a photograph of one of the samples that had been in the ALT for one week before it was peel tested on the Instron machine.


**Figure 9**: DGO-1 coated flat bar ALT sample after peel testing. This sample was overmolded with PR-420 primer and PR-1547 polyurethane and had spent one week in the 66°C ALT under cathodic delamination conditions before it was peel tested. The greenish material attached to the right side of the PR-1547 is DGO-1 that has debonded from the metal coupon in a quasi-"window-frame" like pattern.

The peel testing results from DGO-1 coated, flat-bar samples exposed to cathodic delamination conditions during the ALT were the best that had been obtained to date from any combination of coating/primer/polyurethane for monel 400 alloy substrates. The amount of DGO-1 debonding from the metal substrate was the smallest seen out of all other samples for which a polymer coating or primer was directly applied to the monel 400 alloy substrate. In addition, the DGO-1 coated samples were the only flat-bar, rectangular samples for which most of the polyurethane remained well-bonded to the metal coupon after spending two weeks in the 66°C (151°F) ALT under cathodic delamination conditions (i.e., the polyurethane exhibited cohesive failure during the peel test).

### *B. Cylindrical Samples*

The promising results obtained from flat-bar, rectangular monel 400 alloy samples coated with DGO-1 suggested that the DGO-1 coating should be subjected to additional testing (including a long-term ALT) using cylindrical substrates

which more closely resembled the real-life end use (i.e., cable connector backshells). The cost of using actual cable/connector hardware was significant enough to instigate the design and development of a "substitute" connector backshell test sample that would also be optimized for the cathodic delamination ALT (i.e., there would be a place to attach a sacrificial zinc anode, and the sample would yield multiple circumferential peel test segments). The design that was adopted has already been described in a previous section of this report; it utilized a solid metal cylinder that was tall enough so that three individual circumferential peel test segments could be obtained from one sample. The sample is completely encapsulated in ¼ of an inch (0.64 cm) of polyurethane, except for the last ¼ inch (0.64 cm) of its top (which was left as bare metal, to simulate the space between the connector encapsulant and the connector face that, in real life, would be occupied by the connector sealing nut). The bare-metal portion of the sample would be the initial location for the generation of hydroxyl anions via the cathodic delamination reaction (equation 1).

Peel testing of the DGO-1 coated cylindrical samples almost always resulted in the circumferential peel strips failing cohesively rather than adhesively. Figure 10 is a compilation of three separate photos illustrating the cohesive failure of a peel strip on a DGO-1 coated cylindrical sample. While it is true that the generation of the peel strip "leaders" (the portion of the strip initially cut free from the cylindrical substrate and held in the jaws of the Instron machine as it applies force to the sample) is not 100% reproducible (the leaders are hand cut by a technician with a razor blade); strip-to-strip variability in thickness and/or defects in the peel strip leaders were not viewed as significant issues. This is especially evident when the results obtained from the DGO-1 coated cylindrical samples are compared to the results obtained from the NCC-coated or the bare metal cylindrical samples (which show obvious evidence of delamination/debonding from one or more substrates). With the exception of the EY18 DGO-1 coated cylindrical sample, no true evidence of debonding by (or from) the DGO-1 coating was ever obtained from any of the long-term DGO-1 coated ALT samples.

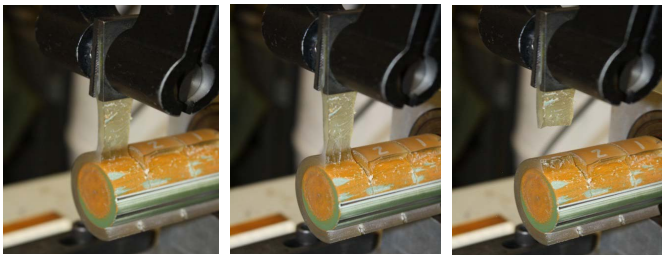

**Fig. 10**. Cohesive failure of a peel strip on a DGO-1 coated cylindrical sample.

Peel strips on DGO-1 coated cylindrical samples removed from the long-term ALT consistently failed via polyurethane cohesive failure (figure 11). The DGO-1 coating itself was never observed to have debonded from the monel 400 cylinders with the possible exception of the most aged samples from the ALT (the EY18 sample; figure 12).

**Fig. 11**. EY16 cylindrical sample with DGO-1 coating after circumferential peel testing. Each of the three polyurethane peel strips failed cohesively.

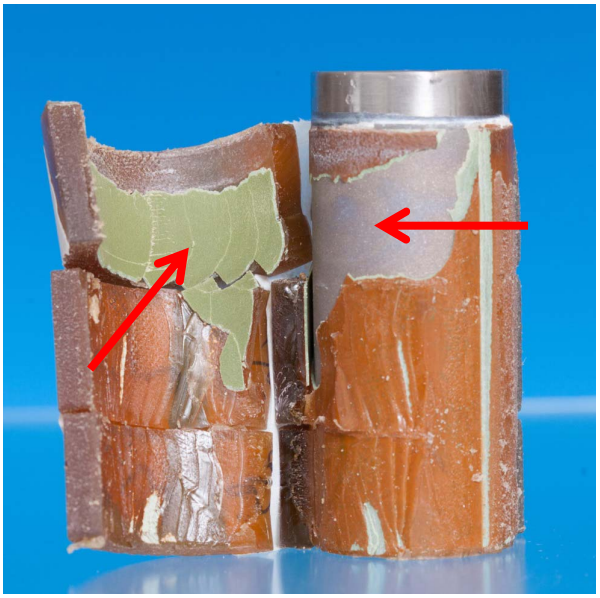

**Fig. 12**. EY18 cylindrical sample with DGO-1 coating after circumferential peel testing. The red arrows point to areas where the DGO-1 coating failed adhesively from the monel 400 alloy.

It is unclear why the failure behavior of the EY18 DGO-1 coated sample is so different from what was observed with identical samples aged between 1 and 17 equivalent years. The measured peel strength of the uppermost peel band on the EY18 sample was 48 pli – which is still a respectable value! Unfortunately, there were only 18 samples in the ALT, so there was no way to determine whether or not the EY18 results were simply a fluke or if the DGO-1 coating had truly reached its survival limit. Still, the fact that the coating lasted for 18 equivalent years under very harsh, cathodic delamination promoting conditions is very impressive. Bare metal cylindrical samples (figure 13) and NCC coated cylindrical

samples (figure 14) fail much more rapidly under the same conditions.

**Fig. 13**. EY2 bare metal cylindrical sample after circumferential peel testing. The blue arrow indicates the extent of the still well-bonded region.

**Fig. 14**. EY5 NCC coated cylindrical sample after circumferential peel testing. The top-most peel band has completely deboned from the NCC coating, and the middle peel band is well on its way to suffering a similar fate. The lower-most peel band is still well bonded and exhibited polyurethane cohesive failure.

## IV. Discussion of Results

The promising results obtained from flat-bar testing of the DGO-1 coating overmolded with PR-420 primer and PR-1547 polyurethane were verified by the outstanding performance of the coating on the cylindrical samples that were subjected to a severe, cathodic delamination-inducing environment during a long-term ALT. The material held its own for 18 equivalent years (about 19 months of real-time) before possibly starting to succumb to the punishing conditions of the ALT.

To demonstrate just how good a performance the DGO-1 coating provided, cylindrical monel 400 alloy samples with NCC coatings (and the new, SealPlus sealcoat) performed much less impressively under the same conditions (actually, in the same ALT tank!). NCC coating with SealPlus sealcoats are considered to be "state-of-the-art" as far as cathodic delamination resistant coatings are concerned, and are widely used in both civilian and military applications to help hardware last as long as possible in cathodic delamination prone environments. After about five years of service, one could expect about two inches (5 cm) of debonding on a connector protected from cathodic delamination via a NCC coating (figure 14), while a connector coated with DGO-1 would not have exhibited any debonding during the same time frame. These results indicate that it is possible to make coatings that are resistant to cathodic debonding. Unfortunately, the composition of the DGO-1 coating is proprietary, and therefore unknown to this author. However, it does provide a starting point for further research into cathodic delamination resistant coatings.

The long-term ALT results for NCC-coated cylindrical samples are an additional piece of evidence suggesting that these coatings are not as resistant to cathodic delamination as they might have been in the past. The problem does not appear to be related to the ceramic itself – it remained well-bonded to the monel cylinders throughout the duration of the ALT. The problem seems to be located at the NCC-primer interface, and may be related to damage inflicted on the seal coat by the high pH of the cathodic delamination environment. The seal coats used on the NCC coatings are typically phenolic resins which are known to be incompatible with high pH solutions. The use of a seal coat that could survive high pH environments could impart greater degradation resistance to NCC coatings in cathodic delamination-prone environments.

One final attribute of the cylindrical samples is that they demonstrate cathodic delamination on outboard cables connectors will proceed from an exposed metal/coating edge, rather than through the coating itself. Although this effect was difficult to track on the DGO-1 coated samples (because they did not significantly degrade during the long-term ALT), it was quite obvious on the cylindrical samples with NCC coatings. On those samples, the first circumferential peel strip failed before the second circumferential peel strip, which failed before the third circumferential peel strip (which was farthest away from the exposed metal/coating edge). Outboard connectors fail in the same manner out in the field (figure 15) and it was gratifying to see that the controlled laboratory experiment essentially duplicated the connector failure mechanism seen in the field. The cylindrical samples can also be used to test more exotic cathodic delamination prevention technologies, such as the use of internal or external bands that rely at least partially on constrictive barrel stress around a cylindrical substrate to stop the debonding process. The design of the cylindrical samples maximizes the available space for

circumferential peel strips while minimizing cost (compared to the cost of using real connector hardware).

**Fig. 15**. Outboard cable connector suffering from cathodic delamination. The dark region on the backshell under the polyurethane overmold has already debonded; only the orange portion of the backshell is still bonded. Note that the debonding has proceeded inward from the exposed metal/coating edge.

## V. CONCLUSIONS

DGO-1 coatings have survived for 18 equivalent years in a long-term, heated (66°C/151°F) seawater ALT under conditions designed to actively promote cathodic delamination. The coating exhibited no signs of debonding from the underlying monel 400 alloy substrate until the last equivalent year of the ALT; prior to that, all of the sample failures were caused by substrate failure (polyurethane cohesive failure). The observed resistance of the DGO-1 coating to cathodic delamination is significantly better than all other coatings/materials that have been tested to date, including the NCC coatings presently used by the Navy on marine hardware located in cathodic delamination prone environments. The superior performance of the DGO-1 coating in the ALT compared to NCC coatings (even with the improved SealPlus sealcoat) is quite evident from figures 11, 13 and 14. Significant debonding of the PR-420 primer from NCC coatings is evident after only two equivalent years of time had passed in the ALT; interestingly, the failure mechanism for NCC coated cylindrical samples in the cathodic delamination promoting ALT matches what has been observed on failed NCC-coated outboard cables returned from the Fleet [4]. Even though the acceleration factor for the ALT used for the experiments described in this report originates from studies of the behavior of bare metal surfaces in cathodic delamination prone environments [5] and, therefore, may be subject to revision if future research provides a better estimate of the Arrhenius activation energy for the cathodic delamination process, the long amount of time spent by the DGO-1 samples in the ALT without significant evidence of debonding (while other samples – NCC coated and bare metal were debonding rapidly) reinforces the conclusion that DGO-1 is one of the best coatings that could be applied to hardware subject to cathodic delamination conditions. The long-term performance of the DGO-1 coating with other primers and polyurethanes has not yet been investigated, so the use of primers/polyurethanes other than PRC-DeSoto's PR-420 and PR-1547 in combination with the DGO-1 coating cannot be endorsed at this time.

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