Performance History of Thermal-Sprayed Aluminum Coatings in Offshore Service

Karl P. Fischer
Marine Materials AS, P.O. Box 173, N-3201 Sandefjord, Norway

William H. Thomason
Conoco Inc., P.O. Box 1267, Ponca City, OK 74603

Trevor Rosbrook
Salamis JV Ltd., Salvesen Tower, Blaikes Quay, Aberdeen A B1 2PW, UK

Jay Murali
Conoco Norway Inc., P.O. Box 488, N-4001, Stavanger, Norway

In 1984, the Hutton TLP was installed with a sealed thermal-sprayed aluminum (TSA) coating. After eight years of service, the TSA coating on the production risers and tethers was still in good condition. The condition in the splash zone was indistinguishable from other inspected components. However, there were notable differences between the production risers and the tethers. The tethers, having a vinyl sealer, showed a blistered surface, while the risers, with a silicone sealer, did not show any blistering. No corrosion has been observed underneath any of the blisters. The importance of adequate sealers in connection with blistering has been documented by testing. The excellent performance of TSA coating in the splash zone is further documented by field studies published in the last few years.

Initial confidence in the splash-zone performance of the thermal-sprayed aluminum (TSA) coating for the Hutton TLP was based on results of in-house salt fog tests, the experience of the American Welding Society (AWS) and the US Navy, and information from the British Standard Institution.1-3 The AWS study evaluated various parameters such as coating thickness, surface preparation, and sealer coatings in long term exposures in several environments. Sealed TSA-coated panels (80 microns) at Wrightsville Beach, North Carolina, showed no damage to the underlying steel after 19 years exposure.1

The main result from the US Navy study was the successful performance of a 125 micron unsealed TSA coating after a 15-year exposure and a 100 micron TSA coating after 18-1/2 years (Port Hueneme Harbor, California).2

A 1977 British Standard (BS 5493) stated that sealed TSA will protect steel from corrosion for 20 years or longer without maintenance in seawater splash-zones.3 It should be noted that the TSA coatings in 1977 would not be the same quality as those used today.

TSA's Successful History

Since the Hutton TLP installation in 1984, more experiences on TSA coating's long-term performance have been documented.

Both 80 and 150 micron aluminum (Al) coatings showed no corrosion of the steel substrate after 34 years of exposure at the LaQue Centre (Kure Beach, North Carolina) test site. Several metal coatings performed extremely well in the marine atmosphere. While several alloys (aluminum-zinc [Al-Zn] or aluminum-magnesium [Al-Mg]) performance depended on the gun applicators, the 100% Al coating was least affected.4

Bethlehem Steel Corp. documented the results of 25 years of experience with Al-Zn alloys coatings, also tested at LaQue. The time to first rusting of the substrate was 15 years for severe marine (25 m from the ocean) and 25 years for moderate marine (250 m from the ocean). This was the case for alloys with a 45 to 70% Al content; data on a pure Al coating is not described.5

The Norwegian Institute for Air Research published the results of metalized steel exposed 14-1/2 years in a marine splash zone (Tananger, Norway). A 160 micron TSA coating had visible but in significant damage.

Experience with thermal-sprayed coatings in the Soviet Union showed that a 120 micron Al coating could perform effectively for 20 to 25 years in salt water. A 150 micron thick dual Zn-Al coating (5 microns of Zn and 145 microns of Al) could last 40 years or more in a humid atmosphere. Corrosion rates for 99% Al in seawater and the splash zone were 4 and 0.009 microns/y, respectively. This would imply a service life of 50 years or more in a seawater or splash zone environment for a 200 micron coating.7

Testing at SINTEF, Norway, in natural seawater, gave free corrosion rates of 2 to 3 microns/y after 11 months of exposure for both 99.5% Al and Al-5%Mg. This would imply a service life in excess of 60 years for a 200 micron TSA coating.8

A four-year program off the coast of Germany (southern North Sea) exposed 99.5% Al, 200 microns thick, in the submerged and splash zones. From the results it was predicted that the Al coating would have a minimum 10-year service life in seawater.

The U.S. Army conducted long term tests on various organic and metallic coatings at Buzzard's Bay, Massachusetts (18 years exposure) and at La Costa Island, Florida (21 years). The tests at Buzzard's Bay exposed "H" piles 9.1 m long in seawater. TSA with and without sealer (vinyl Al) were exposed. The TSA coating thickness was in the range 80 to 120 microns. Some of the pilings were made with holidays (2.5 by 15.2 cm) spaced at 1.2 m along the pile. After 18 years of exposure, there were several bare areas in the splash zone as well as dense blistering on the TSA-coated piles. There was no rust undercutting in the holiday areas. The TSA-coated pile with sealer was evaluated to give equal to slightly superior protection as compared to the TSA without sealer. The TSA coating was rated to be the best of the 24 systems tested at Buzzard's Bay.

At LaCosta Island, the tests used the same "H" piles as the Buzzard's Bay site. After 10 years, the piles were inspected. For the TSA coating (150 microns) without a sealer, light scale and rust were present all along the pile. Corrosion was most severe in the splash zone, probably because of the porous nature of the coating with no sealer. For the TSA coating with a sealer (vinyl), stains and rust were present only in the atmospheric zone. The coating was in excellent condition in the immersed zone. The coating was in good condition after the 10 years because the sealer filled the porosity in the TSA coating.

The US Navy approved the use of TSA coatings in 1981 as standard DOD-STD-2138 (SH) for naval ships. For high-temperature service (780 degrees C), a 250 to 375 micron coating with two coats of a heat-resistant Al sealer is applied; and adhesion strength of 13.8 MPa (2,000 psi) is specified. This coating is expected to give more than 10 years service.

The first use of TSA coating for offshore platforms in the North Sea was for flare booms. Today the use of TSA has increased significantly. Statoil now specifies a TSA coating (Al- 5%Mg with a sealer) for the following applications:

- thermally insulated surfaces of tanks, vessels, and piping;
- flare booms;
- crane pedestals;
- crane booms;
- lifeboat stations and supports;
- all carbon steel on undersides of cellar decks, including piping, etc;
- all carbon steel with operating temperatures of 60 to 450 degrees C.

Use of TSA Coatings on the Hutton TLP

In June 1984, the Hutton tension leg platform (TLP) was installed in water 146 m deep in the North Sea. The tethers, risers, and flare boom were TSA coated. (Background and evaluations of the TSA system have been published earlier).

The TSA coating was a 99.5% Al flame-sprayed coating with 1,000 psi (6.9 MPa) adhesion. The coating was sealed with two coats of vinyl sealer on the tethers and silicone sealer on the risers. One tendon was removed in 1986 and a production riser was removed in 1987 for inspection. There were distinct differences in the TSA coating on the production risers and the tethers. The tethers exhibited blistering and the riser did not. The tether's vinyl sealer may have reacted with or not fully penetrated the TSA coating. Despite the blisters, the TSA coating was in excellent condition with no measurable reduction in coating thickness or evidence of corrosion damage to the substrate.

Table 1 - TSA Thickness Survey (microns) on Production Riser Joint after Eight Years of Service

Maximum Thickness	Minimum Thickness	Average Thickness	Joint Serial No.
401	186	240.61	JJ0240
372	158	219.28	1015 REJECT
248	171	206.69	HH0359
264	180	216.50	HH0084
322	55 (A)	211.44	0321
274	165	223.61	0066
261	143	208.81	1020
372	147	232.94	990055
365	123 (B)	236.89	1040
285	182	225.50	1033
301	173	238.06	1044
285	171	213.89	0213
286	202	242.53	1022

(A) Outlier: Possibly because of local damage; surrounding areas measured 110 to 243 microns.
(B) Outlier: Surrounding areas measured 214 to 253 microns.

Visual inspection by video cameras of the splash zone have revealed no deterioration in coating quality or performance, nor any corrosion damage. High-pressure water jetting (4,000 psi [27.6 MPa]) has been used to remove fouling to enable better inspection (no antifouling coating has been applied). This strong mechanical impact has not caused any coating deterioration.

Survey and Inspection of Hutton TLP Risers

In June 1992, after eight years of service, the Hutton riser strings were visually surveyed and photographed. No corrosion was detected in the splash zone. Such an inspection generally will reveal only serious damage or deterioration in the splash zone. However, studies have shown a brownish bleed-through effect if corrosion has occurred on the substrate. This effect would be very visible against the Al background, and it has not been observed on the Hutton.

One riser string was retrieved due to a workover of a well. The string was sent to shore for complete inspection of wall thickness, inside and outside surfaces, coating, and thread treatment. The following detailed inspections and documentations were performed.

Visual inspection of surfaces -- The general condition of the surfaces was excellent, and areas that exhibited handling marks were indicative of the coating's resilience in that no significant penetration was evident (Fig 1[all figures available upon request]). It is considerably significant that these areas had been exposed to the elements and showed no deterioration. Of particular importance is the fact that the condition of the splash-zone joint was indistinguishable from that of joints in submerged or atmospheric service.

Coating thickness measurements -- Coating thickness surveys around the circumference and along the length of the riser joint measured at or above specified thickness (200 microns), indicating no degradation since installation (Table 1). Again, the data verified that the condition of the splash-zone joint was indistinguishable from the rest.

Destructive adhesion tests -- Adhesion strength was determined by a pull-off method. The adhesion strength between the dolly and the TSA coating was 500 psi (3.5MPa), but the TSA coating adhesion to the steel was better than this value. The typical adhesion strength of the coating during manufacture was of the order of 1,500 to 2.000 psi.

Coating adhesion was also tested using the scribe test, which indicated that the TSA coating adhesion on this riser was excellent. In a few cases, flaking did occur. The spline area of the riser showed no flaking though, indicating the excellent adhesion and physical integrity of the TSA coating (Figure 2 [all figures available upon request]).

Removal of TSA coating to examine the substrate -- The steel substrate was examined after the coating was removed by chemical means. The substrate was in pristine condition with the original blast profile still intact. This indicated that the underlying steel was never exposed to the elements.

Electrochemical potential of TSA -- Annual potential surveys were performed on the risers and tethers. The risers were electrically connected to the hull, which was cathodically protected with an impressed-current system (ICCP) to potentials ranging from -1,050 to -1,120 (Ag/AgCl). The subsea template was protected by sacrificial anodes. As shown in Figure 3 (all figures available upon request), the potential of the risers varied with depth due to the influence of the ICCP system, which drives the top half of the risers around 40 mV move cathodic. Note the more negative potentials in 1992.

The tethers were electrically isolated from any external CP systems by rubber flex joints at both ends. The tether potentials represented the potential of TSA- coated steel and did not vary significantly with depth. Tether readings in 1985 ranged from -980 to -1,000mV (Ag/AgCl). In 1993, tether potentials ranged from -880 to -910 mV.

Performance and Planned Use of TSA on Other Offshore Structures

Conoco and other operators have specified the use of TSA for critical service corrosion protection for several North Sea and Gulf of Mexico projects.

Based on the good experience with TSA on Hutton, TSA was used for splash-zone protection for nine platforms in the southern North Sea, installed in 1987 and 1988. The splash-zone coatings were 200 microns thick with50 microns dry film thickness polyurethane sealer systems. The sealer consisted of a polyvinyl butyral etch primer overcoated with polyurethane. Pinholes occurred in the polyurethane if the etch primer was not used. Subsequent annual splash-zone inspections have revealed no damage to the TSA, and the sealer has performed well. TSA was also selected to protect the risers on the Joillet platform in the Gulf of Mexico in 1989, and no coating problems have occurred.
Recent southern North Sea projects specified TSA for splash zone, riser, and underside of main decks as a means to reduce future maintenance.

The largest offshore application of TSA is planned for the Heidrum TLP which has a 50 year design life. TSA is specified on Heidrun for risers, tethers, deck undersides, and many applications where reliability, low maintenance, and long service are critical. A corrosion allowance will be provided for the Heidrun risers in the splash zone to comply with Norwegian Petroleum Directorate Rules and Regulations (NPD).

High-Temperature Performance of TSA Coating in the Splash Zone

Earlier electrochemical tests of TSA coatings have been performed at the Marine Materials seawater laboratories at steel temperatures up to 60 degrees C. In the splash-zone testing, the samples were exposed in a flow channel to a 6-hour cycle fully submerged, followed by 6 hours half-submerged. The flow rate was 0.1 ms-1. The high and low water level was cycled during a period of 65 days with all the samples freely corroding. The samples were exposed at ambient temperature and at 8, 20, and 60 degrees C. The samples showed minor or no deterioration of the TSA coating after 65 days. The minor deterioration, defined as one to five spots of white corrosion products on the TSA coating sample area of 0.004 m2, did not have measurable pit depths. None of the samples blistered or spalled. In the vicinity of the holidays (10% defect), adhesion was lost. The holiday areas were covered with calcareous deposits, and no sign of corrosion was found. The final potentials for the TSA coated samples after 65 days were -970 and -985 mV, for a sample with no defect and a sample with a 10% holiday respectively.

Test at temperatures from 70 to 100 degree C were also performed. The scope of testing included freely corroding TSA-coated steel as well as anodically and cathodically polarized samples. In addition, blistering behavior was documented to establish data on the anodic and cathodic properties of hot steel with TSA coating.

Materials and Methods for the Splash-Zone Testing

The previous splash-zone tests showed that the narrow transition zone (that area of the sample between the area fully submerged and the area exposed to air) was the area of the TSA coating where salt and calcareous deposits accumulated. This would constitute the low- tide situation in service. The area of the samples simulating wet/dry cycles (tidal area) exhibited insignificant degradation and fewer deposits as compared to the low-tide situation. Considering that such salt accumulations would constitute a worse case situation for coating degradation, a constant water-level exposure (simulating low tide) was applied in the present one year splash-zone test. The intention of this test was to establish how TSA coating with and without a sealer would behave at high temperatures (70 to 100 degrees C) in the splash zone. For the purpose of these tests, it was assumed that the transition zone (fully submerged/air) is the critical zone for corrosion in the splash zone. However, the aspects of physical impact in the splash zone was not considered in this laboratory test.

The test was based on exposing pipe spools of 200 and 110 mm in diam partly submerged in seawater. The use of two pile diameters was to establish if different surface curvatures would influence blistering. The pipes were cut in lengths of 180 mm, and a steel plate was welded to one end. The external surface was then grit-blasted (aluminum oxide grit) and TSA-coated in accordance with the Hutton specification, flame-sprayed to 200 microns thickness. A silicone sealer was used as for the risers on the Hutton (two sealer coats: first coat, 1.5 to 1 thinner to sealer; second coat, 1 to 1 thinner to sealer). The sealer was a silicone Al. Some TSA coatings without sealers were also tested. The adhesion value requirements were in excess of 1,000 psi (6.9 MPa).

The pipes were internally fitted with a heating mantle in a segment of the pipe surface. For the 220 mm pipe this covered a 90-degree segment, while for the 110 mm pipe it covered a 180-degree segment (Figure 4 [all figures available upon request]). The height of the heating mantle was 120 mm. The area isothermally heated was 0.0192 m2 for both the 220 and 110 mm pipe. The brass heating mantle was machined to be mounted with four cartridge heat elements of either 600 or 800 W. The heating was controlled by a J-thermocouple fixed with a measuring point 1 mm from the steel/TSA coating interface. A heat conductive paste on the heat mantle ensured an even heat flux to the steel pipe wall. As the testing was related to the heated TSA coating, the major part of the "cold" pipe was coated with four coats of a vinyl tar.

All calculated current densities refer to the TSA-coated surface (with or without sealer), and a small polarization current to the vinyl tar-coated part of the pipe was neglected. The segment of the pipe in the area of the heat mantle was isothermally heated at a given temperature (70, 85, or 100 degrees C). Outside the edge of the heat mantle, there was a thermal gradient zone (TGZ). Because of the cooling of pipe by seawater, the temperature very quickly decreased outside the isothermally heated zone (IHZ). At a distance of 5 mm outside the mantle, the temperature had decreased by 50%. The pipes were placed in a 640 L tank of seawater with a once through circulation of about 35 L/min. Four to five pipes were exposed in two tanks for more than a year. Because of the large amount of water, the seawater was not heated more than 2 to 3 degrees C during testing. Four circulation pumps increased the mixing of the seawater. The samples were placed so that about 145 mm of the pipe length was submerged and 35 mm was above water level to simulate a splash zone. The seawater was natural seawater fed into the tank on a once-through basis. The quality of the seawater is described in Table 2.

The exposure program was based on freely exposed samples and potentiostatic polarization (Table 3). The samples were polarized by individual potentiostats using platinum wires as auxiliary electrodes and Ag/AgCl reference electrodes. In a measurement using a Luggin capillary a few mm from the TSA surface, it was found that the potential around the whole circumference was within +/-5 mV of the potential set by the potentiostat in the range -900 to -1,000 mV.

Table 2 - Seawater Quality in Splash-Zone Testing

Factor	**Mean**	**Minimum**	**Maximum**
Temperature (^oC)	7.35	4.5	13.2
Salinity (1/1,000)	34.21	33.1	35.5
pH	7.91	7.64	8.20
O_2 (ppm)	10.06	7.4	12.0
Resistivity (ohm-cm)	22.17	21.5	23.7

Monitoring and Inspection During Splash-Zone Testing

The pipe spools were exposed in the tanks at the given temperature and potentiostatic polarization. The polarization current density was monitored daily. The blistering was documented by weekly visual observation with an underwater looking glass. Photographs taken of the blisters through this looking glass avoided having to remove the samples from the tank. After the exposure, coating adhesion was determined with a hydraulic tester.

Table 3 - Splash-Zone Exposure Program and Documentation of Blistering Behavior

Sample Coating Type	Temp (^oC)	Pipe Diam (mm)	Potential mV, Ag/AgCl	Total Exposure Period (Days)	Occurance of Blistering (Days) Location (A)
High-quality FSA without sealer	70	110	~1,100	77	66 (IHZ)
	85	110	-1,100	45	22 (IHZ)
	100	110	-1,100	81	30 (IHZ)
	100	110	-1,100	69	20 (IHZ), 61 (TGZ)
	70	110	-900	202	None
	85	110	-900	139	70 (IHZ), few blisters
	100	110	-900	196	None
	100	110	-900	196	125 (TGZ), 166 (IHZ)
	70	220	-1,100	67	22 (IHZ)
	85	220	-1,100	69	32 (IHZ)
	100	220	-1,100	81	43 (IHZ)
	100	220	-1,100	32	20 (IHZ)
	70	220	-900	202	174 (TGZ), 196 (IHZ)
	85	220	~900	202	None
	100	220	-900	196	125 (TGZ), 187 (IHZ)
	85	220	-900	139	57 (TGZ, IHZ)
	70	110	-900	139	85 (TGZ, IHZ)
High-quality FSA with sealer (B)	70	110	Free corr	83	None
	70	110	Free corr	83	None
	100	110	Free corr	83	None
	100	110	-900	90	None
	100	110	-1,100	348	None
	100	220	-700	83	None
	100	220	-700	72	None
	100	220	-700	419	None
	100	220	-900	127	None
	100	220	-1,100	419	None

(A) Location of blisters on the pipe is as follows: IHZ - in the isothermally heated zone, TGZ - in the thermal gradient zone.
(B) Sample with 10% holiday.

Test Results

The 27 pipe spools were tested for periods of one to 14 months (Table 3). No deterioration was found for the freely corroded pipes in the splash zone exposed in the temperature range 70 to 100 degrees C. The most significant effect was the difference in the blistering behavior of the TSA with and without a sealer.

Corrosion Behavior

For the freely exposed pipe spools, no localized deterioration could be observed in the seawater/air interface. For the freely corroding TSA-coated steel with silicone sealer and coating damage, there were no corrosion products apparent on the coating after the one to 14 month exposure at 70 to 100 degrees C. During an initial period of one month or so, the free corrosion potential at the high temperature was significantly more negative than at ambient temperature (Table 4). In the first few days, the TSA potential was in the range of -1,050 to -1,100 mV Ag/AgCl. However, after a month or so, the potential became more positive. After three months, both high temperature and an ambient TSA-coated surface had a free corrosion potential of about -950 mV Ag/AgCl. A pipe spool with a 10% holiday in the IHZ did not show any corrosion in the bare steel area. Here the steel is polarized and calcareous deposits formed, reducing the current required for maintaining the polarization of the bare steel area. White Al-oxides along the edge of the holiday showed that the TSA coating had functioned as an anode.

Polarization of the TSA to -900 mV Ag/AgCl gave anodic dissolution and the formation of Al-oxides as irregular nodules over the TSA surface. However, the dissolution of the TSA coating was strongly dependent upon conditions on the pipe surface. The dissolution was concentrated in the low-temperature part of the TGZ. Thus, only a minor part of the dissolution at -900 MV occurred in the IHZ (70 to 100 degrees C). A similar effect also occurred for the pipes polarized to -700 mV. Here the most intense anodic dissolution occurred in a narrow band (1 to 2 cm) along the TGZ. The anodic dissolution rate at the temperatures in the range of 70 to 100 degrees C was very variable the first month or so. The current output from the TSA surface was between 350 and 1,400 mA/m2, and to around 50 mA/m2 after six months at -900 mV. Obviously the current output from the TSA coating will be limited by the amount of active Al present (3.0 A-h/cm2 of TSA coating) (Figure 5 [all figures available upon request]).

The cathodic polarization of TSA at 70 to 100 degrees C at -1,100 mV Ag/AgCl showed a decreasing current density with time (Table 5). The initial current densities (first week) were in the very broad range from 60 to 400 mA/m2. After a month, the values had decreased to a mean value of 70 mA/m2, and further decreased to a value of 30 mA/m2 after one year's exposure.

Blistering Behavior

The 10 TSA coated spools with the silicone sealer did not develop blisters after a 14 month exposure at 70 to 100 degrees C (Table 3). However, 14 of the 17 spools with TSA coating without sealer developed blisters. The eight spools polarized cathodically to -1,100 mV Ag/AgCl developed blisters within two months over the whole IHZ (two to three blisters per square centimeter). No blistering occurred in the TGZ. For the TSA coating without sealer exposed at -900 mV Ag/AgCl, the blisters were located in the TGZ and/or in a band along the edge of the IHZ. In most cases, the blistering started in the TGZ and with time also developed in the IHZ.

Table 4 - Free Corrosion Potentials of TSA as a Function of Temperature

	Potential, mV Ag/AgCl		
Temperature (^{o}C)	**Initial (Day 1-2)**	**1 Month**	**3 Months**
8 (ambient)	-800	-1,000	
70	-1,040	-970	-945
100	-1,115	-950	-950

TSA Adhesion Strength

The adhesion strength was specified to be 1,000 psi (6.9 MPa) for the Hutton TLP; however, generally it was higher (2,300 psi, 16 MPa). In this test, very high adhesion values were found (Table 6). The adhesion values were in the range 12 to 18 MPa for the unexposed TSA-coated spools. However, for the exposed TSA, the adhesion values were also in the range of 12 to 18 MPa for spools exposed at -900 and -1,100 mV. None of the 57 measurements gave an adhesion value lower than the specified value of 6.9 MPa. Adhesion values in areas with blisters also were consistently high, showing that the area adjacent to a blister did not suffer reduced adhesion.

Other Considerations

The approach to splash-zone protection is by either thin-film or thick-film coatings. Depending on design requirements, a corrosion allowance is usually needed when using a thin-film coating (for example, coal tar epoxy or glassflake epoxy). If a thick-film coating (for example, neoprene or copper-nickel sheathing) is used, a corrosion allowance may not be required.

For the Hutton TLP, the TSA coating has been used without a corrosion allowance. For the planned Heidrun TLP in the Norwegian Sea, the design for splash-zone protection includes TSA coating (200 microns) with a corrosion allowance. Current regulations classify TSA as a thin-film coating; therefore, the splash-zone corrosion allowance was provided to meet the safety precautions of the NPD.

However, on the basis of the experiences and data reported here, we believe that a 200 micron TSA coating applied with today's state of the art technology will have a service life in excess of 30 years in a splash zone.
However, to achieve such a service life, certain critical factors need to be considered and optimized:

- TSA alloy,
- surface preparation
- TSA coating application
- choice and application of sealer
- service application
- electrochemical/galvanic exposure situation, and
- environmental impact.

The choice alloy for splash-zone or submerged service would be either Al (99.5%) or Al-5% Mg. Using Al-Zn alloys would increase the anodic capabilities while decreasing the barrier properties. This would not be optimal for the splash zone because the high dissolution rate for an Al-Zn alloy would lead to a rapid breakdown of the coating.

Table 5 - Cathodic Current Density on Hot TSA-Coated Steel at 70-100 ^{o}C, Polarized to -1,100 mV Ag/AgCl (A)

	Current Density, mA/m^2		
Time	**Mean**	**Maximum**	**Minimum**
Initial (first week)	180	400	65
1 month	70	165	30
1 year	30	55	10

(A) 11 pipes were tested.

For good performance system, stringent requirements for the surface preparation and application are required. The use of a sealer is vital. The sealer must completely penetrate and fill porosity of the TSA coating, but the sealer will not build any thickness. A two-coat silicone Al sealer will perform best for ambient service. The sealer will also prevent blistering.

In Europe, the costs of a TSA coating Al and Al-5% Mg to 200 micron thickness could be in the range $60 to $200 per square meter, averaging around $140 per square meter. The wide range in cost may be related to differences in the specification requirements in the offshore industry.

Table 6 - Adhesion Values Determined by Hydraulic Adhesion Tester

	Isothermally Heated Zone 2			Adhesion (Mpa) (A)	
Potential mV Ag/AgCl	70 ^{o}C	85 ^{o}C	100 ^{o}C	Thermal Gradient Zone 1- 2^{o}/linear mm	Mean Adhesion Values at Various Potentials
Free Corrosion	14.5 S		14.5 S		14.7
	15.0 S				
-900	16.5	15.5	14.5 S	14.0 B	15.38
	15.5	16.0	16.0 S	16.5 B	
	15.5 B	21.0	14.0 S	16.5 B	
	17.5	18.0	12.0 S+	12.5 B	
		16.0	11.5 S	12.5	
		17.0	12.0	16.0	
			15.5		
			15.5		
			13.0		
			16.5		
-1,100	17.0 B	14.5	14.5 S	18.0	13.95
	12.0 B	18.0 B	16.5 S	14.5	
	10.5 B	14.0 B	13.0 S	16.0 B	
	16.0 B	12.5 B	7.5 S	14.5 B	
	12.5 B	11.5 B	13.5 S	17.5 B	
			17.0 S	15.5 B	
			16.0 S	11.5 B	
			10.0 S	14.5	
			9.5 S		
			12.5 S		
Unexposed surface	18.5 S, 16.0 S, 12.0 S, 14.0 S				15.00

(A) The "pull off" failure was in the glue with one exception. S denotes TSA with sealer; + denotes edge broke down to bare steel; B denotes blisters in the dolly area.

The basic property of the TSA coating as a long-service coating is its barrier characteristics combined with good adhesion and mechanical strength. However, in an exposure situation where the TSA coating surface is electrically connected to bare steel, anodic dissolution of the TSA coating can be extensive. Here the anodic current capabilities of the TSA coating need to be considered. Based on a TSA current capacity of 3.0 A-h/cm2, a 200 micron thick coating could sustain a 4% area of bare steel for 30 years. (In this calculation, a 50 mA/m2was used as a current demand for the bare steel and a 2,000 A-h/kg capacity for the Al at a 0.8 utilization factor.) However, if a TSA-coated steel is connected to bare steel with a 1 to 1 area ratio, the coating could be completely deteriorated after three to four years. The Hutton risers and tendons have a nearly 100% coated surface. Because of the excellent mechanical and adhesion properties, the TSA coating has not been scraped off during handling and service; thus, there are few holidays.

Conclusion

TSA coatings have now become an established system for the protection of offshore and marine structures.

The experiences from Hutton and other projects have shown that TSA coating with an adequate sealer will perform well in the splash zone at both ambient and high-temperature conditions (70 to 100 degrees C).

Experiences from the Hutton TLP and laboratory testing established that a silicone sealer will prevent blistering. Blistering also is dependent on the electrochemical state of the TSA surface and the temperature gradients on the pipe surface.

It can be predicted that a service life in excess of 30 years for splash-zone service is achievable with a 200 micron TSA coating applied according to present state of the art technology.

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