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THE EFFECTS OF CO-MINGLING DISSIMILAR FASTENER COATINGS ON THE CORROSION BEHAVIOR OF STEEL BOLT ASSEMBLIES

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ABSTRACT

Accelerated corrosion tests were carried out to assess the performance of selected coated fastener assemblies representative of those used in the M1A1 tank and Bradley fighting vehicle (coated grade 8 steel bolts fastened to armor steel and Al 5083 blocks). The coatings tested included the currently used electroplated cadmium and zinc as well as proposed electroplates of Zn-Ni, Zn-Co, Sn-Zn and a zinc phosphate modified polyacrylic acid conversion coating. The effect of co-mingling cadmium with the other coatings in the various assemblies was determined. Salt spray testing was performed in accordance with ASTM B117. In addition salt water immersion tests were performed and continuously monitored by electrochemical potential measurements. Breakaway torque values obtained after completion of either immersion or salt spray tests were correlated with coefficient of friction measurements. Cadmium electroplate exhibited the best corrosion protection for grade 8 steel bolts in salt spray or immersion tests. The zinc-nickel coating was the best overall alternative to cadmium plate. The modified zinc phosphate conversion coating was clearly unacceptable. Co-mingling of cadmium with the other coatings did not create a galvanic corrosion problem. Loosening of the Zn and Zn alloy coated fasteners will not likely occur when Cd torque values are used.

CONTENTS

Background

During a 1987 inventory assessment of Grade 8 fasteners, Defense Logistics Agency (DLA) discovered a widespread substitution of zinc for cadmium electroplating. In order to maintain the highest readiness posture possible DLA obtained Army concurrence to use zinc plated fasteners except for certain critical airborne equipment. Concurrence by the Air Force and Navy to accept zinc as a legitimate alternative to cadmium for grade 8 fasteners was also obtained in late 1987. As a consequence BG Raffiani, Jr., Deputy Commanding General, AMCCOM in response to a request by MG Pigaty, Commander, DLA, initiated the necessary action on 22 February 1988, to change the plating requirement for MS-18153, MS-18154, MS-90727 and MS-90728 grades 8 fasteners from cadmium plating to zinc plating in accordance with ASTM-B-633, Type II, Class Fe/Zn 8 or cadmium plating in accordance with QQ-P-416, Type II, Class 3. TACOM, AMSTA-QLS, by Memorandum of 7 October 1988, agreed to the change only for Hexagon Head Cap Screws. Also agreed upon for the zinc plated fasteners was the continued use of torque charts for wet or dry combinations based on cadmium fasteners and contained in the present system's manuals and maintainence instructions. For selected electrical or electronic applications where cadmium plated fasteners are required or preferred the design agency should specify Cd plating for these fasteners. Co-mingling of zinc plated fasteners with cadmium plated fasteners was not expected to cause problems in the field. On 21 October 1988 a coordination meeting was held at HQAMC with LTG J.M. Bunyard, DCGRDA, LTG F. Hissong, DCGMA, MG L. Pigaty, Cdr Defense Industrial Supply Center (DISC) and representatives from MTL, TACOM and AMCCOM. After lengthy discussion all participants agreed to (1) no hazard to troops existed because of intermingling cadmium and zinc plated fasteners (2) tech manual changes for torque requirements were not needed except for a few isolated cases and (3) the DISC proposal to change military standard Grade 8 drawings to require zinc plating. The DCGRDA directed AMC to adopt zinc as the standard plating.

Since that time corrosion concerns for mingling of dissimilar fastener platings by prime contractors and the military have been expressed. For example, the Marine Corp is vitally concerned that the mixture of zinc and cadmium plated fastener hardware may have a potentially critical impact on the durability, reliability and maintainability of the M1A1/Abrams Tank. Specifically, the Marine Corp operating environment of frequent exposure to salt spray and salt water immersion of components will "exacerbate the inherent galvanic corrosion problems which mixing zinc and cadmium plated fastener hardware causes". In addition, many technical manuals will be inaccurate because of differences in torque values for Zn and Cd plated hardware in the same application. Also, the General Dynamics Land Systems Division has implied that there is a critical problem with galvanic corrosion from the use of Zn plated bolts with Cd plated nuts and washers based on the failure of Wear Plate Bolts (studs), P/N 12274490, on a M1A1 Swedish demonstration vehicle. It should be noted that this wear plate bolt problem is not typical of all bolts and MS-fasteners used on the MIAI. Further, FMC Corp. forsees production problems in attempting to couple zinc plated fasteners to aluminum alloys and has proposed the use of zinc-nickel plating as an alternative to zinc plating. As a consequence AMSTA-T has attempted to draft a TACOM policy to cover procurement of fasteners for current military vehicle production and field replacements but has not achieved consensus. They believe that the projected RAM-D impacts of mixing hardware should not be a major concern and have issued instructions to the Army in the field to continue to use the torque values for fasteners which are currently provided in technical manuals. Since current field supplies may have co-mingled Cd and Zn plated bolts, this plan is the most suitable for insuring the accuracy and reliability for torquing fasteners based on tests performed by DISC and TACOM. Nevertheless TACOM would like to resolve the issue and requested MTL to carry out a test program which would verify and support the above mentioned TACOM bolt policy for current or future procurement of military vehicles.

Scope of Work

The test program and fasteners assemblies developed by G. MacAllister, AMSTA-ZCF, and M. Levy, SLCMT-EMM are described in Appendix A.

Materials

All bolts were fabricated of SAE Grade 8, J429 steel, HRC 33-39 (Figure 1) and meet the requirements of MS-90728. In material and dimensions, the nuts and washers were compatible with the grade 8 bolts. The two blocks in (assembly) Joint A (Figure 2) are fabricated of SAE Grade 4130 steel, HRC 32-34. (Actual hardness value HRC 30 measured by Engineered Heat Treat Inc.). The chemical analysis is shown in Table 1. Table 2 contains the chemical analysis of the armor steel described in MIL-A-12560, class 1 used in Joint B (HRC 28-33) in conjunction with 4130 steel (Figure 3).

	Table 1	Table 2
Species	w/o	w/o
Carbon	0.32	0.28
Manganese	0.49	1.36
Phosphorous	0.013	0.016
Sulfur	0.002	0.001
Silicon	0.23	0.23
Chromium	0.97	0.12
Nickel	0.09	0.09
Molybdenum	0.23	0.47
Vanadium	<0.01	<0.01
Boron	<0.0005	0.002
Iron	base	base

The chemical analysis for the aluminum alloy AA5083 used in Joint C in conjunction with armor steel is shown in Table 3. (Figure 4.)

	Table 3
Species	w/o
Copper	<0.05
Iron	0.35
Silicon	<0.15
Manganese	0.55
Magnesium	4.2
Nickel	<0.05
Chromium	0.10
Titanium	<0.15
Tin	<0.05
Zinc	<0.09
Aluminum	base

Cadmium plating was processed in accordance with QQ-P416 Type II Class 3 and bake, minimum thickness 0.0002 in. The zinc plating was processed in conformance with ASTM B633 Type II, olive drab and bake, minimum thickness 0.0002 in. Both plating operations were performed by Cadillac Plating Corp. The Zn-Co plating was processed by OMI International Corp. as described in Table 4. The alloy plating contained 0.62 to 0.81% Co and the thickness ranges between 0.0002 and 0.00037 in. FMC processed the Zn-Ni plating in accordance with their proposed specification covering the requirements for electrodeposited zinc-nickel alloy plating Class 3, Type II, minimum thickness 0.00030 in. (see Appendix B). The Zn-Ni alloy plate is 6-20% Ni. The new phosphate coating developed and processed by Sugama and Kukacka, Brookhaven National Laboratory, Upton, NY, introduced polyacrylic acid macromolecules into the phosphating solution to improve the stiffness and moisture impermeability of the crystalline zinc phosphate layers.

Table 4

Operation	Conditions	Time
Soak Clean	UDYPREP 108	10 minutes
Electro Clean	UDYPREP 263	6 minutes
C.W.R.*		
Acid Bath	50%HCl	6 minutes
C.W.R.*		
ZINCROLYTE Plate	.0002-.0003 In.	
Current Density	7.5A/ft2	30 minutes
C.W.R.*		
Dry		
Bake	400F	4 hours
Activate	UDYPREP 345 4 oz/gal	5 seconds
C.W.R.*		
Dry		

* Cold Water Rinse (CWR)

The Sn-Zn plating was performed by Dipsol Gumm Venture employing their neutral Sn-Zn process in accordance with the procedure described in Table 5. This alloy plating is comprised of 70-80% Sn, the balance Zn with a thickness of 0.0003-0.0004 inches. Note that the coated part cannot be given a baking treatment for hydrogen embrittlement relief because of the low melting point of the Sn-Zn alloy.

Table 5

Operation	Process	Concentration	Temp	Time
Soak Clean	Clepo 136-R	12 oz/gal	140-160F	5 min
Rinse				
Electroclean	Clepo 60-MM	12 oz/gal	140-160F	2 min
Rinse				
Acid Pickle	Hydrochloric acid	40%	Room Temp.	6 min
Rinse				
Electoclean	Clepo 60-MM	12 oz/gal	140-160F	5 min
Rinse				
Activate	Hydrochloric acid	10-20% b.v.	Room Temp	1 min
Rinse				
Plate	Tin-Zinc (SZ-240) Rack	15-20 ASF	70-80F	18 min
Double Rinse				
Chromate	SZ-248 Yellow	35 ml/Liter	70-90F	40 sec
Rinse				
Dry	Hot air		under 150F	10 min.

Experimental

Accelerated corrosion tests were carried out to assess the performance of the galvanic couples described in Appendix A. Salt fog testing was performed in accordance with ASTM B117. Observations were made and recorded every 24 hours of exposure up to 312 hours. In addition, salt water immersion tests (3.5% NaCl solution) were performed in a circulating bath at 25C with corrosion monitored continuously by electrochemical potential measurements (see Figure 5) and observations made every 24 hours up to 312 hours of exposure. Photographs of the fastener assemblies were taken before and after testing to show the degree of corrosion developed. Photomicrographs of the cross-section of the plated washers were taken to show the thickness, uniformity and contiguity of the various platings.The coefficient of friction of the various platings were determined by the CSEM Revetest Scratch Tester, where a moving diamond stylus "scratches" the plated surface under either constant or linearly increasing load. This instrument is equipped with an integrated optical microscope, an acoustic emission detection system and a device to measure the tangential frictional force (in the scratching direction), from which the friction coefficient value is determined during scratching. Breakaway torque values for Joints A, B, C were obtained after either immersion and salt spray tests were completed.

Results

Salt Spray, Controls (Figure 1)

The specifications for both electrodeposited coatings of zinc and cadmium require that these treatments shall show neither their white corrosion products nor basic metal corrosion products at the end of 96 hours of salt spray exposure.

Table 6 contains observations made for the various coated control assemblies as a function of exposure time. Supporting photographs are contained in Figures 6-11. The cadmium coated components showed no evidence of corrosion products (white or red rust) even after 312 hours of exposure (Table 6, Figure 6). Zinc plating, which was approved as an alternative to cadmium plating for grade 8 fasteners, provided protection for 96 hours, after which white corrosion products appeared in increasing amounts. Approximately 70% of the component surfaces were covered with white corrosion products at the end of the test (Table 6, Figure 7). The performance of the Zn-Ni coating, the first of a series of newer coatings being evaluated for military applications, is described in Table 6 and Figure 8. This coating protected the bolt, nut and washer assembly for 192 hours although some staining was observed after 96 hours of exposure. White corrosion products appeared during the exposure period 216-312 hours. The Zn-Co coating performed as well as the Zn coating. White corrosion products appeared after 96 hours of exposure and at 312 hours the coverage had spread to 65% of the component surfaces (Table 6, Figure 9). The Sn-Zn coating showed no evidence of corrosion products for the first 144 hours. Thereafter appreciable gray corrosion products (which turn white when dried) appeared and slight rusting of the steel occurred (Table 6, Figure 10). The super phosphate coating which incorporated polyacrylic acid molecules into the phosphate treatment provided no corrosion protection to the control assembly. Rust spots appeared after only 6 hours of exposure and corrosion exacerbated thereafter until 80% of the components were covered with rust (Table 6, Figure 11). In summary, the coatings may be ranked in the following order of decreasing protection: Cd, Zn-Ni, Zn-Co, Zn, Sn-Zn, super phosphate. Clearly cadmium was the best performer, followed by Zn-Ni. Zn, Zn-Co, Sn-Zn performed comparably and marginally met the 96 hour salt spray requirement. The super phosphate coating obviously was unacceptable.

Salt Spray, Joint A

The Joint A assembly has been described schematically in Figure 2. Note that both blocks of the assembly were fabricated of 4130 steel. For each assembly the bolt, washer and nut were coated with the same material. Table 7 summarizes observations made as a function of time exposure for a total of 312 hours. Figures 12-17 contain supporting photographic evidence. Cadmium plate again was the best performer (no corrosion products 312 hours) followed by Zn-Ni, Sn-Zn, Zn-Co, Zn and super phosphate in order of decreasing merit. The Zn-Ni plate showed no evidence of white corrosion products for 120 hours of exposure. The Zn and other Zn alloy coatings exhibited small amounts of white corrosion products as early as 72 hours. The super phosphate again began to show red rust after only a few hours of exposure.

Joint A was modified to allow mixing of a Zn, Zn alloy or super phosphate coated bolt with a cadmium plated nut and washer in order to create a potential galvanic corrosion problem. Visual observations and photographs showing the results of exposing such assemblies to salt spray are contained in Table 8 and Figures 18-22. A comparison of the results contained in Tables 7 and 8 show the cadmium plated nuts and washers were largely unaffected by the galvanic coupling in every coupling scheme. Coupling cadmium with zinc appears to have a beneficial effect in diminishing the amount of white corrosion products observed and preventing rusting of the threaded area of the steel bolt. The performance of the Sn-Zn plated bolt was significantly improved by coupling with Cd, particularly at the larger exposure times (168-312 hours). The Zn-Co plated bolt showed some diminution of corrosion attributed to the Cd during the exposure period 72-168 hours and prevented rust from appearing at 240 and 312 hours. There appeared to be little effect of the Cd on the Zn-Ni plated bolt since it remained free of corrosion products for 96 hours. The cadmium plated parts provided no protection to the superphosphated bolt which began to rust after 6 hours of exposure to salt fog.

Salt Spray, Joint B

The Joint B assembly has been described in Figure 3. The two blocks employed in this assembly were fabricated of 4130 steel and Armor Steel, Class 1 (MIL-A-12560). For each assembly the bolt, washer and nut were coated with the same material. Table 9 summarizes the observations made as a function of exposure time. Accompanying photographs are contained in Figures 23-28. The coatings may be ranked in the following order of decreasing merit: Cd, Zn-Ni, Zn, Zn-Co, Sn-Zn, superphosphate. The cadmium provided protection for 312 hours of exposure. The Zn and Zn alloy coatings showed no evidence of corrosion products for 96 hours of salt spray but exhibited white corrosion products thereafter. Rust was observed on the steel coated with superphosphate after only 6 hours of exposure.

Salt Spray, Joint C

This joint assembly has been described in Figure 4. Note the different compositions of the two blocks in the assembly; Armor steel and Al 5083. For each assembly tested, the bolt, nut and washer were coated with the same material. Table 10 summarizes observations made for each coating as a function of exposure time. Figure 29-34 contain corresponding photographs. There was no evidence of white corrosion products or rust for the Cd coated assembly throughout the 312 hours. Zinc and the zinc alloy coatings were free of white corrosion products for 96 hours. White corrosion products appeared thereafter increasing with increasing time of exposure. These coatings may be ranked in the following order of decreasing merit, based on a total exposure time of 312 hours: Cd, Zn-Ni, Sn-Zn, Zn, Zn-Co and superphosphate. Comparing the Joint B assembly data and Joint C assembly data (Tables 9 and 10), it appears the substitution of the Al 5083 block for the steel block diminished the amount of corrosion products observed on the Sn-Zn coated parts over the 168-312 hour exposure period. Also, it increased the observed amount of rusting of the super phosphate coated parts during the first 144 hours of the test.

3.5% NaCl Immersion - Controls

Table 11 contains potential measurements made for the coated control assembled during the course of their immersion in 3.5% NaCl solution. Comments on their appearance as a function of immersion time are also contained therein. Plots of potential as a function of immersion time in days are presented in Figure 35 to show the progress of breakdown of the specific coating applied to the steel bolt washer and nut assembly and follow on corrosion of the basic steel. Photographs of the coated control assemblies before and after immersion for 312 hours complement the potential time data (Figures 36-41). Referring to Fig. 35, the potential of the uncoated steel drops markedly in the more active direction (from -0.231 to -0.624) within a 24 hour period indicative of the onset of corrosion which is confirmed by the first appearance of rust (Table 12). The changes in potential thereafter are minimal and a fairly constant potential (-0.675) is achieved after 7 days of exposure when 50% of the steel surfaces are covered with rust. If the potentials of the coated parts approach or attain this potential then the coating has broken down and exposed the bare steel to active corrosion. The zinc and zinc alloy coatings display initial active corrosion potentials (-1.0V) relative to steel indicating these coatings will provide sacrificial corrosion protection. Zinc and zinc-cobalt coatings show relatively sudden shifts in potential in the more noble direction as they approach the potential of corroding steel after 4-5 days of immersion in chloride solution. The Zn-Ni coating shows a moderate rate of change of potential approaching the potential of corroding steel after 9 days of immersion time. The potential of the Sn-Zn coated steel remains fairly constant for the first six days and thereafter exhibits grey corrosion products and rust as the potential approaches that of the corroding steel. The potential of the superphosphate coated control markedly drops to the potential of corroding steel after one day of exposure and remains relatively constant thereafter as rusting is observed on the bolt, washer and nut. This sudden drop in potential coincides with the first appearance of rust. In contrast, the potential of the cadmium plated parts remains relatively constant (-0.76) throughout the 312 hours of immersion and provides the best protection for the steel substrate. The coated control assemblies may be ranked in the following order of decreasing merit: Cd, Zn-Ni, Sn-Zn, Zn-Co, Zn and superphosphate.

Immersion - Joint A

All possible Joint A coupling schemes were not tested due to the limited number of components available. Potential measurements and observations made during the course of immersion testing of the coated Joint A assemblies are contained in Table 12. Their potentials are plotted as a function of time in Figure 42. Complementary photographs at 0 and 312 hours of immersion are shown in Figures 43-46. The potential of the cadmium coated assembly remained relatively stable throughout the entire test indicative of its excellent corrosion resistance. The potential of the zinc plated assembly began to change after two days of immersion when white corrosion products appeared. Thereafter the potential shifted more dramatically in the direction of the steel potential which was reached after 10 days of exposure and rust was observed. When a cadmium plated nut and washer was incorporated in the Zn plated joint the potential shifted within 48 hours in the more noble direction to the cadmium potential. This joint remained at the cadmium potential until 7 days had elapsed and thereafter increased to the steel potential where it stabilized for the duration of the test. White corrosion products were observed on the Zn plated bolt head and exposed thread area. Some rust was also found on the exposed bolt thread areas and Cd plated washer. The Zn-Ni plated bolt with Cd washer and nut exhibited very little rust on the bolt and washer after 12 days of immersion. This coincided with the potential increasing to that of the steel after an initial rapid increase over the first two days to the cadmium potential. It should be noted that in all cases involving the Zn and Zn alloy coated assemblies gray/white corrosion products were observed within 2 days of immersion. The coated Joint A assemblies may be ranked in the following order of decreasing merit: Cd, Zn-Ni with Cd washer and nut; Zn; and Zn with Cd washer and nut.

Immersion - Joint B

For these joint assemblies potentials and observations are recorded in Table 13, potential-time curves are plotted in Figure 47, and complementary photographs are contained in Figures 48-53. It should be noted that Cd washers were not incorporated in the Zn, Zn alloy and superphosphate coated assemblies due to the unavailability of additional steel blocks. The potential for the Cd plated joint was relatively stable for 10 days and then increased to the steel potential as rusting of the edges of the Cd plated washers was observed. The Cd plated bolt was free of corrosion products. The Sn-Zn and Zn-Co plated joints behaved in a similar manner; potentials shifted markedly within 2 days to the steel potential. Shortly thereafter the Sn-Zn plated bolt began to rust on the bolt head and spread as immersion time increased. Unfortunately, the Zn-Co plated bolt did not seal properly and salt solution leaked into the bolt shaft area causing significant corrosion therein but not permeating into the threaded area of the bolt. The bolt head also rusted dramatically after immersion for 3 days. The Zn-Ni plated joint reached the steel potential after 5 days immersion time when rust was observed on the washers. After seven days of immersion the potential of the Zn plated joint increased to the steel potential where significant amounts of rust appeared on the washers. Uncharacteristically grey/white corrosion products appeared on all the

Zn based coating assemblies within 2 days of immersion time. The superphosphate treated assembly characteristically showed evidence of rust early on (1 day of exposure) as it's potential decreased to that of the steel. The ranking of these coatings for Joint B in decreasing order of protection is: Cd, Zn-Ni, Zn, Sn-Zn, superphosphate, Zn-Co.

Immersion - Joint C

Armor steel and Al5083 blocks were used in this assembly. Again because of the limited number of blocks available Cd washers were not incorporated in assemblies containing the other coatings.

Potential readings and observations are recorded in Table 14. Plots of potential as a function of immersion time are shown in Figure 54. Photographs before and after test are contained in Figures 55-60. The cadmium potential was relatively stable throughout the test and showed no evidence of corrosion. The potentials of the other coatings approached the potential of aluminum within a three day period when white corrosion products formed. There was little or no evidence of rust on any of the assemblies at the conclusion of the test. It appears that the aluminum whose potential is anodic to steel provided sacrificial protection to steel and prevented the formation of rust. Cadmium again is the best performer. The other coatings displayed comparable corrosion resistance.

Breakaway Torques

Tables 15 and 16 contain breaking torque values for the various joints which were exposed to either Saltspray or immersion in chloride solution. It should be noted that the threaded portion of the bolt was lubricated with oil prior to assembly and torquing of each joint. Also that each joint was torqued to 180 ft. lbs. except for those joints involving the Zn-Ni coating where the initial torque was 90 ft-lbs. due to the smaller diameter of the bolt. Generally the superphosphate coated joints exhibited significantly reduced breaking torques indicating the fastener will likely loosen during service. In most cases, the Zn and Zn alloy coatings exhibited breaking torques which were either comparable to or higher than cadmium. Generally little evidence of corrosion was observed in the threaded potion of these coated bolts in the various joints and loosening in service is therefore not anticipated. Also, there was no evidence of stress corrosion cracking due to the combined action of exposure to the chloride environment and the applied tensile stress.

Coefficient of Friction

The frictional force per unit contact area (frictional stress), F_t, between the nut and the washer, or that between the washer and the armor plate, whichever is lower, will guarantee that the assembly remain fastened at the set level. This stress $F_t = \mu^*\sigma'$, where $\mu^*=\tan\phi$ is the friction coefficient (Fig. 61) between the two surfaces in contact and σ' is the normal, compressive stress within the nut and the part of the washer in contact with the nut. This stress is proportional to the tensile stress σ within the threaded rod (bolt).

The friction coefficient $\mu^*=\mu_a + \mu_p$, where μ_a and μ_p are the adhesive and ploughing components, respectively. The adhesive component depends on the intrinsic nature of the coating, namely on atomic bonding, chemistry and mutual solubility between coating and substrate materials and the ploughing component depends on surface roughness and the stress required to shear surface asperities. The friction coefficient was determined by automatic scratch testing, using a 200μm radius diamond stylus, a loading rate $dL/dt=100$ N min^{-1}, a scratching speed $dx/dt=10$ mm min^{-1}, hence a load gradient $dL/dx=10$ N mm^{-1}, where L (N) is applied normal load within the 0-60 N range, x (mm) is distance and t (min) is time. As an example, Figure 62 exhibits the variation of μ^* versus applied normal load for Zn-coated specimens. If F_t is the friction stress required to maintain an appropriate fastening, and two coatings, for example Zn and Cd, are compared, then:

$$F_t = \mu^*_{Zn}\,\sigma'_{Zn} = \mu^*_{Cd}\,\sigma'_{Cd} = \mu^*_i\,\sigma'_i \qquad (1)$$

where μ^*_{Zn} and μ^*_{Cd} and μ^*_i are the coefficients between two Zn, two Cd or two i metal coatings, respectively, and σ'_{Zn}, σ'_{Cd}, σ'_i are the respective compressive stresses within the Zn-coated, Cd-coated and i metal-nuts.

The proportionality between compressive stresses within the nuts and the respective tensile stesses within the bolts, σ_{Zn} and σ_{Cd}, may be expressed by:

$$\sigma'_{Zn} / \sigma'_{Cd} = \sigma_{Zn} / \sigma_{Cd} \qquad (2)$$

hence,

$$\mu^*_{Zn}\,\sigma_{Zn} = \mu^*_{Cd}\,\sigma_{Cd} \qquad (3)$$

These friction coefficients are not readily measurable, whereas those between the diamond stylus and the two coatings are. The ratios of the two groups of coefficients may be assumed to be approximately equal. Hence:

$$\mu^*_{Zn\text{-}Zn} / \mu^*_{Cd\text{-}Cd} = \mu^*_{Zn\text{-}dia} / \mu^*_{Cd\text{-}dia} \qquad (4)$$

In the present case, see Table 17, for virgin, as-coated specimens μ^*_{Zn}=0.488 and μ^*_{Cd}=0.377, hence $\sigma_{Zn} = 0.772\sigma_{Cd}$.Thus the tension inside the Zn-coated bolt that maintains good fastening may be 22.8% lower than that inside the Cd-coated bolt and so may the required torque to achieve the same level of fastening. These conclusions remain valid, if we consider the various friction coefficients following salt-spray or immersion tests in chloride solution. Thus, for salt-sprayed specimens, see Table, 17, μ^*_{Zn}=0.551 and μ^*_{Cd}=0.447, and $\sigma_{Zn} = 0.811\sigma_{Cd}$, and for chloride solution immersed specimens, μ^*_{Zn}=0.424 and μ^*_{Cd}=0.330, and $\sigma_{Zn} = 0.778\sigma_{Cd}$, hence the respective tensions inside the Zn-coated bolts that maintain good fastening may be 18.9% and 22.2% lower than those inside the Cd-coated bolts and so may the required torques to achieve the same level of fastening. Similar calculations show comparable reductions attributable to the following virgin coatings: Zn-Ni 22.8%, Zn-Co 15.3%, and Sn-Zn 11.7%. The superphosphate coating, conversely, will require a 11.2% higher torque to achieve the same level of fastening as the cadmium coated part. These data complement and support the breakaway torque results; loosening of the Zn and Zn alloy coated fasteners will not occur when Cd torque values are used, whereas loosening of the superphosphate coated fastener will most likely occur. Figure 63 contains photomicrographs of the cross-sections of the plated washers. Generally, the platings exceed the thickness requirements and are relatively uniform, contiguous and adherent.

Conclusions

(1) Cadmium exhibited the best corrosion protection for grade 8 steel bolts in salt spray and immersion tests.

(2) The zinc nickel coating was the best overall alternative to cadmium plate and met the corrosion resistance requirements for zinc plating. The zinc, zinc cobalt and tin-zinc coated assemblies did not meet the 96 hour salt fog requirement (no white corrosion deposits or red rust).

(3) The superphosphate coating was clearly unacceptable.

(4) Co-mingling of cadmium with the other coatings in Joint A improved the performance of the Zn, Zn-Co and Sn-Zn coatings and showed little or no effect on Zn-Ni and superphosphate coatings.

(5) The substitution of Al 5083 for one of the steel blocks in Joint C did not diminish the performance of Cd, Zn and Zn alloy coatings when compared to both joints A + B. The presence of the Al 5083 improved the performance of the Sn-Zn and augmented the corrosion observed on the superphosphate treated parts.

(6) Loosening of the Zn and Zn alloy coated fasteners will not likely occur when Cd torque values are used (under wet conditions), whereas loosening of the superphosphate coated fasteners will most likely occur.

Recommendations

(1) Use zinc-nickel plating as an alternative to zinc plating.

(2) Continue to implement the TACOM policy of using the torque values for fasteners which are currently provided in technical manuals regardless of co-mingling of Cd and Zn plated bolts.

Table 6 Saltspray Control Data

Controls						
Hours	Cd	Zn	Zn-Ni	Zn-Co	Sn-Zn	Super Phosphate
6	N	N	N	N	N	Rust Spots
24	N	N	N	N	N	15% Rust Bolt Head, Washer Nut & Threads
48	N	N	N	N	N	20% Rust
72	N	N	N	N	N	40% Rust
96	N	10% White Products	N (Stains)	5% White Products	No Data	50-60% Rust
120	N	30% White Products	N (Stains)	5-10% White Products	No Data	60% Rust
144	N	35% White Products	N (Stains)	15% White Products	No Data	60% Rust
168	N	40% White Products	N (Stains)	15-20% White Products	50% Gray Products 1% Rust	70% Rust
192	N	40% White Products	N	30% White Products	60% Gray Products 1% Rust	75% Rust
216	N	50% White Products	20% White Products	50% White Products	60% Gray Products 1% Rust	80% Rust
240	N	55% White Products	20% White Products	50% White Products	60% Gray Products but Thicker Covering the Rust	80% Rust
312	N	70% White Products	35% White Products	65% White Products	60% Gray Products that turn white when dry	80% Rust

N - No Corrosion

Table 7 Saltspray Joint A (BWN) Data

Joint A's (BWN)						
Hours	Cd	Zn	Zn-Ni	Zn-Co	Sn-Zn	Super Phosphate
6	N	N	N	N	N	Rust Spots
24	N	N	N	N	N	15% Rust
48	N	N	N	N	N	40-50% Rust
72	N	15% White Products Dark Green Spots	N	Few White Products	Gray Spots on Edges Affecting 10%	40-50% Rust
96	N	Dark Green Spots 10%	N	15% White Products and Yellow-Green Stains in the Crevice	No Data	70% Rust, Nut 50% Bolt Head 40% on Threads
120	N	40% White Products and Yellow Stains in the Crevice	N	30-40% White Products and Yellow-Green Stains in the Crevice	No Data	70% Rust All Parts
144	N	45% White & Dark Products and Yellow Green in the Crevice	5% White Products	40% White Products and Yellow-Green Stains in the Crevice	No Data	70-75% Rust
168	N	50% White Products Yellow-Green Stains in the Crevice	5% White Products and Yellow-Green Stains in the Crevice	45% White Products and Yellow-Green Stains in the Crevice	55% Gray Products and Yellow Green Stains in the Crevice	75-80% Rust
192	N	50% White & Dark Products and Yellow Green in the Crevice	5% White Products, Bolt 40% Nut, and Yellow-Green Stains in the Crevice	50% White Products and Yellow-Green Stains 1% Rust Spots	60% Gray Products and Yellow-Green Stains in the Crevice	80% Rust
216	N	50% White & Dark Products and Yellow Green in the Crevice	30% White Products and Yellow-Green Stains in the Crevice	60% White & Dark Products and Yellow Green in the Crevice	70% Gray Products and Yellow-Green Stains in the Crevice	80% Rust
240	N	60% White & Dark Products and Yellow Green in the Crevice	30% White Products and Yellow-Green Stains Covering 40% of Bolt	80% White and Black Products with Yellow-Green, 2% Rust	70% Gray Products and Yellow-Green Stains in the Crevice	80% Rust
312	N	90% White & Dark Products and Now 50% Rust in Threads	35% White Products and Yellow-Green Stains in the Crevice	70% White-Gray Products 15% Rust	85% Gray Products and Yellow-Green Stains in the Crevice	85% Rust

N - No Corrosion

Table 8 Saltspray Joint A w/Cd Data

	Joint A's with Cd				
Hours	Zn with Cd	Zn-Ni with Cd	Zn-Co with Cd	Sn-Zn with Cd	Super Phosphate with Cd
6	N	N	N	N	Rust Spots
24	N	N	N	N	15% Rust
48	N	N	N	N	45% Rust
72	20% Dark Spots on Bolt	N	N	N	45% Rust
96	Dark Green Spots 10%	N	Yellow-Green Stains in the Crevice	No Data	70% Rust Cd Unaffected
120	20-30% White & Dark Products and Yellow Green, Cd Unaffected	20% White Spots on Bolt Head	5% White Products and Yellow-Green Stains Cd Unaffected	No Data	70% Rust Cd Unaffected
144	40% White & Dark Products and Yellow Green, Cd Unaffected	5% White Products Cd Unaffected	10% White Products (Bolt) and Yellow-Green Stains Cd Unaffected	No Data	70% Rust Cd Unaffected
168	40% White Products Yellow-Green Stains Cd Unaffected	5% White Products Yellow-Green Stains Cd Unaffected	10-20% White Products and Yellow-Green Stains Cd Unaffected	3-5% Gray Products and Yellow Green Stains Cd Unaffected	70% Rust Cd Unaffected
192	40% White Products Yellow-Green Stains Cd Unaffected	5% White Products, Bolt Yellow-Green Stains Cd Unaffected	30% White Products and Mixed Dark Stains Cd Unaffected	5% Gray Products and Yellow-Green Cd Unaffected	75% Rust Cd Unaffected
216	40-50% White & Black Products and Yellow Green, Cd Unaffected	20% White Products Yellow-Green Stains Cd Unaffected	70-80% White & Dark Products and Yellow Green, Cd Unaffected	10-15% Gray Products and Yellow-Green Cd Unaffected	75% Rust Cd Unaffected
240	60% White & Black Products and Yellow Green, Cd Unaffected	25% White Products Yellow-Green Stains Cd Unaffected	80% White and Black Products and Yellow Green, Cd Unaffected	15% Gray Products and Yellow-Green Cd Unaffected	80-85% Rust Small Rust Spot on Cd Washer
312	65% Black & White Products and Yellow Green, Cd Unaffected	40% White Products Yellow-Green Stains Cd Unaffected	80% Black & White Products and Yellow Green, Cd Thin on Edges	15% Gray Products and Yellow-Green Cd Unaffected	95% Rust Small Rust Spot on Cd Washer

N - No Corrosion

Table 9 Saltspray Joint B Data

		Joint B's				
Hours	Cd	Zn	Zn-Ni	Zn-Co	Sn-Zn	Super Phosphate
6	N	N	N	N	N	Rust Spots
24	N	N	N	N	N	15-25% Rust
48	N	N	N	N	N	30% Rust
72	N	Dark Green Spots 5%	N	N	Gray Spots on Edges and Yellow Green Stains in the Crevice	40% Rust
96	N	Dark Green Spots 10%	Yellow-Green Stains in the Crevice	5% Dark Stains and Yellow-Green Stains in the Crevice	No Data	40% Rust
120	N	30% White Products Yellow-Green Stains in the Crevice	30% White Products and Yellow-Green Stains in the Crevice	30% White Products and Yellow-Green Stains in the Crevice	No Data	50% Rust
144	N	50% White Products Rust Spots on Bolt Edges	30% White Products and Yellow-Green Stains in the Crevice	45% White Products and Yellow-Green Stains in the Crevice	No Data	60-65% Rust
168	N	50% White Products Yellow-Green Stains in the Crevice	25-35% White Products and Yellow-Green Stains in the Crevice	40-50% White Products and Yellow-Green Stains in the Crevice	30% Gray Products and Yellow Green Stains in the Crevice	70% Rust
192	N	50% White & Dark Products and Yellow Green in the Crevice	40% White Products and Yellow-Green Stains in the Crevice	40% White Products and Yellow-Green and Dark Stains on Bolt	30% Gray Products and 5% Yellow-Green Stains in the Crevice	75% Rust
216	N	50% White & Dark Products and Yellow Green in the Crevice	40% White Products and Yellow-Green Stains in the Crevice	60% White Products and Yellow-Green Stains in the Crevice	30% Gray Products and 10% Yellow-Green Stains in the Crevice	80% Rust
240	N	50% White & Dark Products and Yellow Green in the Crevice	40% White Products and Yellow-Green Stains Covering 40% of Bolt	60-65% White and Black Products with Yellow Green in the Crevice	30% Gray Products and 10% Yellow-Green Stains in the Crevice	80% Rust
312	N	60% White & Dark Products and Yellow Green in the Crevice	65% White Products and Yellow-Green Stains in the Crevice	60% White-Gray Products and Yellow-Green Stains in the Crevice	50% Gray Products and 10% Yellow-Green Stains in the Crevice	80% Rust

N - No Corrosion

Table 10 Saltspray Joint C Data

	Joint C's					
Hours	Cd	Zn	Zn-Ni	Zn-Co	Sn-Zn	Super Phosphate
6	N	N	N	N	N	Rust Spots
24	N	N	N	N	N	50% Rust
48	N	N	N	N	N	50% Rust
72	N	Dark Green Spots 5%	Yellow-Green Stains in the Crevice	N	2% Gray Spots on Edges and Yellow Green Stains in the Crevice	50% Rust
96	N	Dark Green Spots 10% Yellow-Green Stains	Yellow-Green Stains in the Crevice	Yellow-Green Stains in the Crevice	No Data	50% Rust
120	N	30% White & Dark Products and Yellow Green in the Crevice	1% White Products and Yellow-Green Stains in the Crevice	25-30% White Products and Yellow-Green Stains in the Crevice	No Data	70% Rust
144	N	30% White Products Yellow-Green Stains in the Crevice	3% White Products and Yellow-Green Stains in the Crevice	40% White Products and Yellow-Green Stains in the Crevice	No Data	75% Rust
168	N	40% White & Dark Products and Yellow Green in the Crevice	3-5% White Products and Yellow-Green Stains in the Crevice	40% White Products and Yellow-Green Stains in the Crevice	Loss of Chromate Luster and Yellow Green Stains in the Crevice	75% Rust
192	N	30% White Products Yellow-Green Stains and possible Rust	5% White Products and Yellow-Green Stains in the Crevice	40% Gray Products and Yellow-Green Stains in the Crevice	15% Gray Products and 5% Yellow-Green Stains in the Crevice	75% Rust
216	10% Chromate Breakdown No Rust	70% White & Black Products and Yellow Green in the Crevice	5% White Products and Yellow-Green Stains in the Crevice	50% White & Dark Products and Yellow Green in the Crevice	15-20% Gray Products and 10% Yellow-Green Stains in the Crevice	75% Rust
240	40% Chromate Breakdown No Rust	70% White & Black Products and Yellow Green in the Crevice	10-15% White Products and Yellow-Green Stains Covering 40% of Bolt	60% White & Dark Products and Yellow Green in the Crevice	20% Gray & Dark Products and 10% Yellow-Green Stains in the Crevice	80% Rust
312	50% Chromate Breakdown No Rust	80% White & Black Products and Yellow Green in the Crevice	50% White Products nd due to misfit of Blocks, Pink in the Crevice	60% White & Dark Products and Yellow Green in the Crevice	40% Gray Products and 50% Steel Gray and 5% Yellow Green Stains in the Crevice	80% Rust

N - No Corrosion

3.5% NaCl Immersion

Table 11

Joint	Fastener Combination	Comments	Potential	Hours
Control	Cd, BWN	Initial Reading	-0.801	0
		No Change	-0.780	24
		Faded Somewhat	-0.770	48
		Little Fading	-0.768	72
		Little Fading	-0.768	96
		No Change	-0.767	120
		A Spot on the Nut	-0.767	144
		Same Spot on the Nut, No Other Change	-0.767	168
		Few Spots, No Rust	-0.765	192
		Some Products on the Thread	-0.761	216
		Some White Spots, Bubbles on Thread	-0.761	240
		Staining & Frost	-0.752	264
		White Spots on Entire Sample	-0.762	288
		White Spots on Entire Sample + Bubbles	-0.761	312
Control	Modified Phosphate	Initial Reading	-0.461	0
		Small Rust Spots, 1%	-0.578	24
		Small Rust Spots on Threads	-0.591	48
		Rust on Edges 5-10%	-0.598	72
		Rust on Edges 5-10% with Gray	-0.610	96
		10% Rust	-0.612	120
		10% Rust + Grayish Products	-0.625	144
		10% Rust + Grayish Products on Nut	-0.628	168
		10% Rust, More Rust, Less Gray	-0.631	192
		10% Rust + Frost Products on Nut	-0.628	216
		10% Rust + Grayish Products on Nut	-0.631	240
		15% Rust + Grayish Products on Nut	-0.632	264
		20% Rust + Grayish Products on Nut	-0.638	288
		20% Rust & Gray + New Rust in Threads	-0.631	312
Control	Steel, Untreated	Initial Reading	-0.231	0
		25% Rusted	-0.624	24
		35% Rusted	-0.644	48
		40% Rust	-0.653	72
		50% Rust on Body % Edges	-0.661	96
		50% Rust	-0.663	120
		50% Rust & Frost	-0.672	144
		50% Rust	-0.675	168
		70% Rust & Stains	-0.679	192
		85% Rust & Stains	-0.681	216
		90-95% Rusted	-0.683	240
		100% Rusted	-0.685	264
		100% Covered, 50% Deep Rust	-0.686	288
		100% Covered, 50% Deep Rust	-0.663	312
Control	Zn, OD, BWN	Initial Reading	-1.026	0
		40% White Zn products	-0.994	24
		80% White Products	-0.975	48
		5% Rust in Addition to 90% Zn Products	-0.936	72
		95% Mixed Rust and Zn Products	-0.872	96
		95% Mixed Rust and Zn Products	-0.649	120
		100% Rust and Zn Products	-0.656	144
		100% Rust and Zn Products	-0.658	168
		More Rust, Less Zn Products, 100%	-0.654	192
		100% Rust and Zn Products	-0.645	216
		100% Rust and Zn Products	-0.646	240
		100% Rust and Zn Products	-0.652	264
		100% Rust and Zn Products	-0.652	288
		100% Rust and Zn Products	-0.646	312

3.5% NaCl Immersion

Table 11 Continued

Joint	Fastener Combination	Comments	Potential	Hours
Control	Zn-Co, BWN	Initial Reading	-1.021	0
		2% White Corrosion Products	-1.023	24
		70-75% White Products	-0.993	48
		15% Rust and 85-90% Gray Zn Oxides	-1.021	72
		97% Mixed Rust and Zn Products	-0.944	96
		99% Mixed Rust and Zn Products	-0.906	120
		100% Rust and Zn Products	-0.740	144
		100% Rust and Zn Products	-0.664	168
		More Rust, Less Zn Products, 100%	-0.687	192
		100% Rust and Zn Products	-0.698	216
		100% Rust and Zn Products	-0.700	240
		100% Rust and Zn Products	-0.705	264
		100% Rust and Zn Products	-0.705	288
		100% Rust and Zn Products	-0.700	312
Control	Zn-Ni, 1/2" BWN	Initial Reading	-0.980	0
		5% White Products	-0.973	24
		50% Covered w/White Products	-0.945	48
		60% Grayish White Zn Products	-0.936	72
		60% Grayish White Zn Products	-0.875	96
		75% Grayish White Zn Products	-0.827	120
		75% Grayish White Zn Products	-0.785	144
		95% Grayish White Zn Products	-0.750	168
		95% Products, No Rust	-0.701	192
		95% White Zn Products	-0.656	216
		100% White Zn Products, No Visible Rust	-0.640	240
		95% White Zn Products, 5% Rust	-0.633	264
		100% White Zn Products, 10% Rust	-0.629	288
		100% White Zn Products, 10% Rust	-0.629	312
Control	Sn-Zn	Initial Reading	-1.023	0
		No Change	-1.004	24
		Lightly Frosted - 30%	-1.013	48
		Gray Spots on Surface	-1.009	72
		No Reading	--	96
		Gray Spots Covering 50%, Small Rust Spots	-0.933	120
		60-65% White & Gray Zn Products, Rust Stains	-0.985	144
		60% Gray Products with Orange Stains	-0.975	168
		Gray Covering 75%+ and 15% Rust	-0.960	192
		75% Gray Products, 20% Rust Stains	-0.942	216
		80% Gray Products, 20% Rust Stains	-0.912	240
		90% Zn Products, 30% Rust	-0.898	264
		95% Zn Products, Rust Showing Through 40%	-0.850	288
		95% Zn Products, Rust Showing Through 40%	-0.772	312

3.5% NaCl Immersion

Table 12

Joint	Fastener Combination	Comments	Potential	Hours
Joint A	Cd, BWN	Initial Reading	-0.796	0
		No Change	-0.774	24
		Faded with Dark Spot on Bolt Head	-0.767	48
		One Dark Stain, Otherwise Slight Fading	-0.767	72
		Some Spots, Otherwise no Change	-0.766	96
		Some Spots, Otherwise no Change	-0.764	120
		A Large Spot on Bolt Head, Rust	-0.763	144
		No Change, Same Spot	-0.762	168
		Rust Spotting Bolt Head, 15% Breakdown	-0.760	192
		Nut Flaking, No Rust	-0.756	216
		Nut Flaking, Head is Darker	-0.755	240
		No Change	-0.756	264
		30% Cd Flaking Away	-0.754	288
		30% Cd Flaking Away	-0.754	312
Joint A	Zn OD Bolt, Cd W & N	Initial Reading	-1.043	0
		Gray Spots on Bolt, Cd Faded	-0.988	24
		White Products on all Parts	-0.898	48
		50% Gray on all parts, rust in crevice	-0.750	72
		85% Products on Bolt, 60% on Cd	-0.755	96
		85% Products on Bolt, 60% on Cd	-0.755	120
		85% Products on Bolt, 65% on Cd	-0.751	144
		100% Products on Bolt, 70% on Cd	-0.736	168
		100% Products, Bolt-Black,Nut &Washer-White	-0.672	192
		100% Products on Bolt, 70% on Cd	-0.727	216
		100% Zn + Rust on Bolt, 70% Gray on Cd	-0.688	240
		100% Bolt,100% White on Cd	-0.681	264
		100% Bolt, 100% Gray on Cd	-0.674	288
		100% Bolt, 100% Gray on Cd	-0.674	312
Joint A	Zn OD, BWN	Initial Reading	-1.049	0
		85% Gray Bolt, Nut & Washer	-1.052	24
		White Products Coating 80%	-0.998	48
		70% Whitish Gray Products	-1.003	72
		90% Whitish Gray Products	-0.990	96
		90% Whitish Gray Products	-0.966	120
		90% Whitish Gray Products	-0.942	144
		100% Orange Tinted Products	-0.906	168
		100% Orange Tinted Products	-0.859	192
		100% Orange Tinted Products	0.770	216
		100% Orange Tinted Products	-0.665	240
		100% Orange Tinted Products	-0.668	264
		100% Rust Tinted Products	-0.673	288
		100% Rust Tinted Products	-0.665	312
Joint A	Zn-Ni Bolt, Cd W & N	Initial Reading	-0.974	0
		Small Stains on Bolt, Cd very Faded	-0.979	24
		Cd Chromate 100% Faded	-0.863	48
		60% Gray on Bolt, Cd faded 100%	-0.821	72
		75% Gray on Bolt, Cd faded 100%	-0.756	96
		75% Gray on Bolt, Cd faded 100%	-0.760	120
		75% Gray on Bolt, Cd Shows Gray Frost	-0.759	144
		75% Gray on Bolt, Cd Shows Gray Frost	-0.753	168
		90% Gray on Bolt, Cd Shows Gray Frost	-0.752	192
		75% Gray on Bolt, Cd Shows Gray Frost	-0.692	216
		85% Gray on Bolt, Cd Shows Gray Frost	-0.692	240
		85% Gray on Bolt, Cd Shows Gray Frost	-0.686	264
		100% Gray & Rust on Bolt, Cd Frosted	-0.697	288
		100% Gray & Rust on Bolt, Cd Frosted	-0.692	312

3.5% NaCl Immersion

Table 13

Joint	Fastener Combination	Comments	Potential	Hours
Joint B	Cd Bolt	Initial Reading	-0.789	0
		Slight Yellow Chromate Fading	-0.781	24
		Faded Like Control	-0.775	48
		Same as Control	-0.772	72
		Same as Control	-0.767	96
		Same as Control	-0.764	120
		Same as Control	-0.761	144
		No Change	-0.759	168
		No Change	-0.756	192
		Thin Frost	-0.735	216
		Some Discoloration	-0.673	240
		Washers 35% Rusted, Bolt - OK	-0.704	264
		Washers 70% Rusted, Bolt Unaffected	-0.702	288
		Washers 70% Rusted, Bolt Shows Slight Discoloration	-0.702	312
Joint B	Modified Phosphate	Initial Reading	-0.617	0
		Rust Spots on Bolt Edges	-0.655	24
		Rust on Bolt Edges, 3%	-0.663	48
		5% Rust on Edges, Gray Spots on Washer	-0.665	72
		5% Rust on Edges, Spots on Washer	-0.667	96
		5% Rust on Edges, Spots on Washer	-0.668	120
		5% Rust on Edges, White on Washer 60%	-0.669	144
		10% Rust on Edges, White on Washer 95%	-0.668	168
		10% Rust on Edges, Rust on Washer 90%	-0.667	192
		10% Rust on Edges, Rust on Washer 95%	-0.665	216
		10% Rust on Edges, White on Washer 99%	-0.667	240
		10% Rust on Edges, White on Washer 95%	-0.667	264
		15% Rust on Edges, White on Washer 95%	-0.666	288
		15% Rust on Edges, White on Washer 100%	-0.666	312
Joint B	Zn, OD Bolt	Initial Reading	-1.059	0
		Gray Products on Bolt Surface	-1.038	24
		Grayish Tan Products Covering 80%	-1.024	48
		80% Grayish-Yellow, 1% Rust	-1.019	72
		80% Tan Products, 1% Rust	-1.010	96
		80% Tan Products, 1% Rust	-1.000	120
		80% Products, Yellow, 1% Rust	-0.980	144
		80% Products, Yellow, 1% Rust	-0.946	168
		90% Products, Orange, 1% Rust	-0.865	192
		100% Rust & Zn Products	-0.681	216
		100% Rust & Zn Products	-0.684	240
		100% Rust & Zn Products	-0.688	264
		100% Rust & Zn Products	-0.691	288
		100% Rust & Zn Products	-0.691	312
Joint B	Zn-Co Bolt	Initial Reading	-1.025	0
		Few Dark Stains	-1.025	24
		White Products on 50% Area	-0.699	48
		White Products Gone, 75-80% Rust	-0.682	72
		90% Rust	-0.690	96
		95% Rust	-0.692	120
		95% Rust	-0.692	144
		100% Rust	-0.690	168
		100% Rust	-0.692	192
		100% Rust	-0.690	216
		100% Rust	-0.689	240
		100% Rust	-0.690	264
		100% Rust	-0.689	288
		100% Rust	-0.689	312

3.5% NaCl Immersion

Table 13 Continued

Joint	Fastener Combination	Comments	Potential	Hours
Joint B	Zn-Ni, 1/2" Bolt	Initial Reading	-1.016	0
		Few White Products	-1.014	24
		Whitish Tan Products 50%	-0.968	48
		60-70% White Products	-0.883	72
		60% Tan Products	-0.785	96
		65% Tan Products	-0.736	120
		65% Tan Products	-0.636	144
		65% Tan Products, Auxilliary Washer 100%	-0.659	168
		100% Sacrificial Products, Rusted-Washer	-0.671	192
		65% Tan Products, Auxilliary Washer 100%	-0.677	216
		Head Rust Spreading, Auxilliary Washer 100%	-0.689	240
		65% Tan Products, Auxilliary Washer 100%	-0.681	264
		65% Tan Products, Auxilliary Washer 100%	-0.681	288
		65% Tan Products, Auxilliary Washer 100%	-0.681	312
Joint B	Sn-Zn	Initial Reading	-1.023	0
		Bubbles on Bolt	-0.973	24
		Many Bubbles, No Corrosion, Bolt is Cathode	-0.638	48
		Bolt Head 50% Corroded	-0.640	72
		No Reading	--	96
		505 Rust on Bolt Head	-0.664	120
		50-55% Rust on Bolt	-0.666	144
		50-55% Rusted on Bolt	-0.675	168
		60% Rusted on Bolt	-0.669	192
		60% Rust on Bolt	-0.669	216
		60% Rust on Bolt	-0.666	240
		60% Rust on Bolt	-0.667	264
		80% Rusted & Stained on Bolt	-0.668	288
		80% Rusted & Stained on Bolt	-0.668	312

3.5% NaCl Immersion

Table 14

Joint	Fastener Combination	Comments	Potential	Hours
Joint C	Cd Bolt	Initial Reading	-0.787	0
		No Change	-0.785	24
		No Change	-0.793	48
		Same as Control	-0.799	72
		Same as Control	-0.805	96
		Same as Control	-0.808	120
		Same as Control	-0.810	144
		Tinted Darker to a Coppertone	-0.812	168
		No Change	-0.812	192
		No Change	-0.810	216
		Darker but no Rust	-0.810	240
		No Change	-0.816	264
		No Change	-0.820	288
		No Change	-0.810	312
Joint C	Modified Phosphate	Initial Reading	-0.750	0
		No Visible Corrosion, Bolt is Cathode	-0.778	24
		No Rust Sighted	-0.783	48
		No Rust, Bolt is Cathode	-0.782	72
		20% Gray Products	-0.780	96
		20% Gray Products	-0.782	120
		20% Gray Products, Mostly on Edges	-0.784	144
		20% Gray Products, Mostly on Edges	-0.782	168
		20% Gray Products, Mostly on Edges	-0.780	192
		20% Gray Products, Thin Frost	-0.772	216
		20% Gray Products, Thin Frost	-0.778	240
		20% Gray Products, Slight Rust	-0.783	264
		20% Gray Products, Traces of Rust	-0.782	288
		20% Gray Products, Traces of Rust	-0.778	312
Joint C	Zn, OD Bolt	Initial Reading	-1.023	0
		Slight Spotting on Bolt	-1.053	24
		5% Dark Stains	-1.026	48
		10% Dark Spotting	-0.835	72
		10% Dark Spotting	-0.780	96
		10% Dark Spotting (Not Bad)	-0.791	120
		10% Dark Spotting with Fade (Not Bad)	-0.800	144
		10% Dark Spotting with Fade (Not Bad)	-0.806	168
		Some Orange Products, 50%	-0.811	192
		10% Dark Spotting with Frost (Not Bad)	-0.815	216
		10% Dark Spotting with Frost	-0.816	240
		Frosted	-0.822	264
		10% Dark Spotting with Frost (Looks OK)	-0.823	288
		10% Dark Spotting with Frost (Looks OK)	-0.816	312
Joint C	Zn-Co Bolt	Initial Reading	-1.025	0
		Bubbles on Bolt Head	-1.053	24
		55% White Products	-1.035	48
		25% White Products	-0.989	72
		30-40% White Products	-0.791	96
		40% White Products	-0.781	120
		40% White Products with Orange Tint	-0.793	144
		70% White Products with Orange Tint	-0.797	168
		70% White Products with Orange Tint	-0.799	192
		70% White Products with Orange Tint	-0.799	216
		70% White Products with Orange Tint	-0.810	240
		70% White Products with Rust Tint	-0.809	264
		70% White Products with Rust Tint	-0.818	288
		70% White Products with Rust Tint	-0.810	312

3.5% NaCl Immersion

Table 14 Continued

Joint	Fastener Combination	Comments	Potential	Hours
Joint C	Zn-Ni, 1/2" Bolt	Initial Reading	-0.974	0
		Crevice Corrosion Under Bolt Head	-0.920	24
		Gray Products on 15% Bolt	-0.780	48
		25% Gray Products	-0.789	72
		25% Gray Products	-0.794	96
		25% Gray Products	-0.800	120
		30-40% Gray Products	-0.803	144
		70-80% Gray Products	-0.804	168
		70-80% Gray Products, Rust in Crevice	-0.778	192
		70-80% Gray Products, Rust in Crevice	-0.808	216
		70-80% Gray Products, Rust on Edges	-0.810	240
		100% Gray Products, Rust Stains 20%	-0.783	264
		100% Gray Products, Rust on Edges	-0.814	288
		100% Gray Products, Rust on Edges	-0.810	312
Joint C	Sn-Zn	Initial Reading	-1.023	0
		At the Potential of Al	-0.792	24
		Small Spots - 5%	-0.791	48
		Some Corrosion at Bolt Head/Nut Interface	-0.804	72
		No Reading	--	96
		Black on Bolt Head & in Crevice, Scattered Rust Spots	-0.803	120
		Same as Previous with a Hint of Frost	-0.809	144
		As with Previous with Slightly more Frost	-0.813	168
		New Rust Spots, Black in Crevice Turned to Rust, - 7%	-0.820	192
		Rust Spots, Black in Crevice Fading to An Orange Rust	-0.819	216
		Rust Spots, Faded in Crevice	-0.816	240
		Rust Spots, Faded in Crevice	-0.814	264
		Few Rust Spots, Dark Rust in Crevice	-0.817	288
		Few Rust Spots, Dark Rust in Crevice	-0.824	312

Table 15

Saltspray Breakaway Torques

Joint A's

Fastener	Breakaway Torque (ft-lbs)
Modified Phosphate (BWN)	116.7
Modified Phosphate w/Cd Nut & Washer	133.3
Cd (BWN)	125.0
Zn OD (BWN)	158.3
Zn OD w/Cd Nut & Washer	133.3
Zn-Co (BWN)	166.7
Zn-Co w/Cd Nut &Washer	133.3
Zn-Sn (BWN)	150.0
Zn-Sn w/Cd Nut & Washer	150.0
Zn-Ni (BWN)*	75.0
Zn-Ni w/Cd Nut & Washer*	75.0

Joint B's

Fastener	Breakaway Torque (ft-lbs)
Modified Phosphate	116.7
Cd	141.7
Zn OD	133.3
Zn-Co	166.7
Zn-Sn	141.7
Zn-Ni*	75.0

Joint C's

Fastener	Breakaway Torque (ft-lbs)
Modified Phosphate	150.0
Cd	150.0
Zn OD	175.0
Zn-Co	166.7
Zn-Sn	166.7
Zn-Ni*	91.7

*Zn-Ni Fasteners used smaller bolts with initial torquing at 90.0 ft-lbs

Table 16

Immersion Breakaway Torques

Joint A's

Fastener	Breakaway Torque (ft-lbs)
Cd (BWN)	141.7
Zn OD (BWN)	133.3
Zn OD w/Cd Nut & Washer	158.3
Zn-Ni w/Cd Nut & Washer*	66.7

Joint B's

Fastener	Breakaway Torque (ft-lbs)
Modified Phosphate	108.3
Cd	133.3
Zn OD	175.0
Zn-Co	158.3
Zn-Sn	158.3
Zn-Ni*	66.7

Joint C's

Fastener	Breakaway Torque (ft-lbs)
Modified Phosphate	141.7
Cd	133.3
Zn OD	166.7
Zn-Co	166.7
Zn-Sn	150.0
Zn-Ni*	66.7

*Zn-Ni Fasteners used smaller bolts with initial torquing at 90.0 ft-lbs

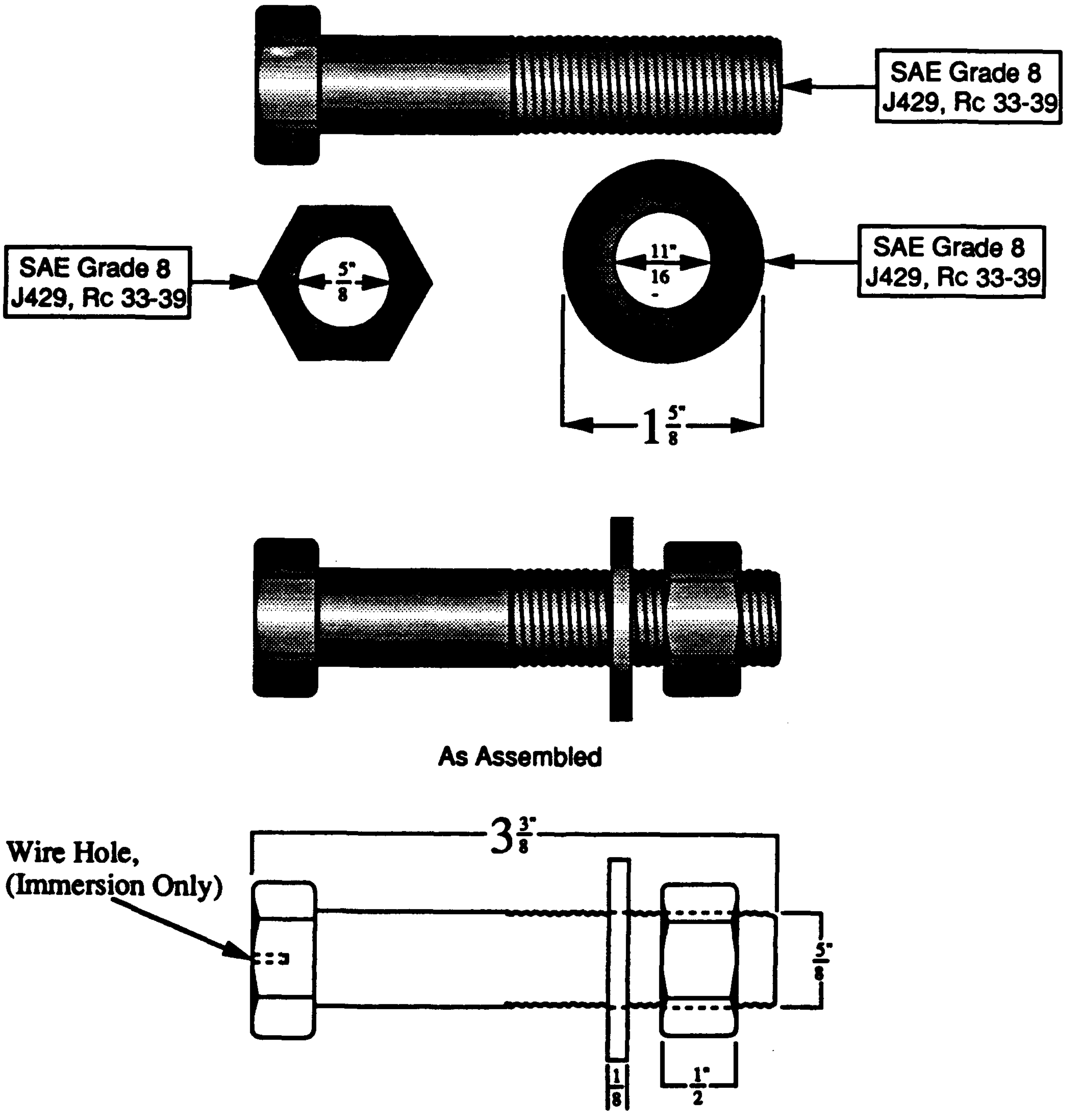
TABLE 17

AVERAGE FRICTION COEFFICIENTS, μ^*, OF COATED SPECIMENS

Coating	Virgin	Salt Spray	Immersion in Chloride Solution
Zn-Ni	0.532	0.472	0.422
Zn-Co	0.445	0.467	0.496
Zn-Sn	0.427	0.287	0.406
Cd	**0.377**	**0.447**	**0.330**
Mod. P	0.355	0.286	0.237
Zn (OD)	**0.488**	**0.551**	**0.424**
Steel Substrate	0.277		

Fig. 1

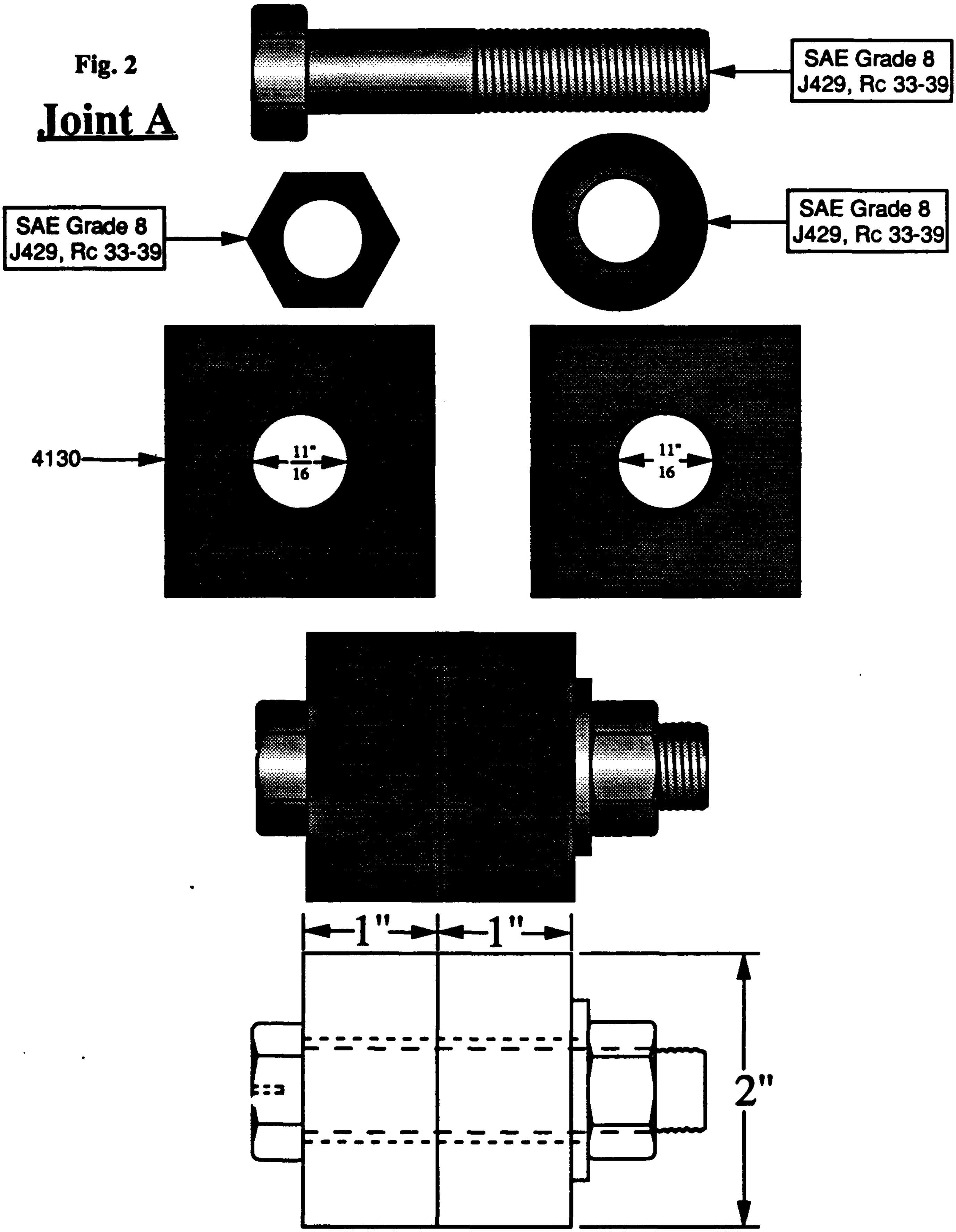
Controls



Cross-Section

Fig. 2

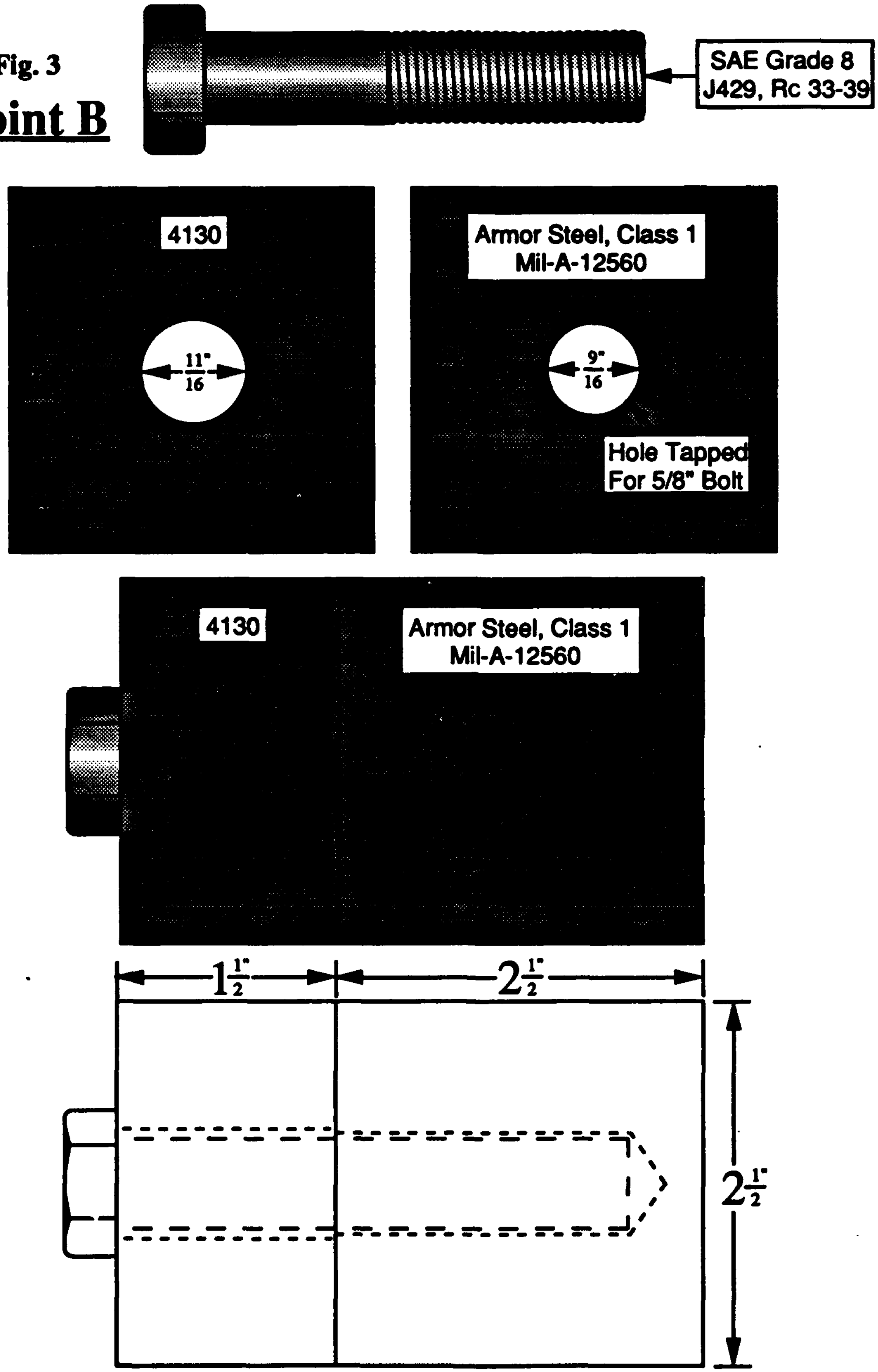
Joint A



See Controls for Bolt & Nut Dimensions

Fig. 3

Joint B



See Controls for Bolt & Nut Dimensions

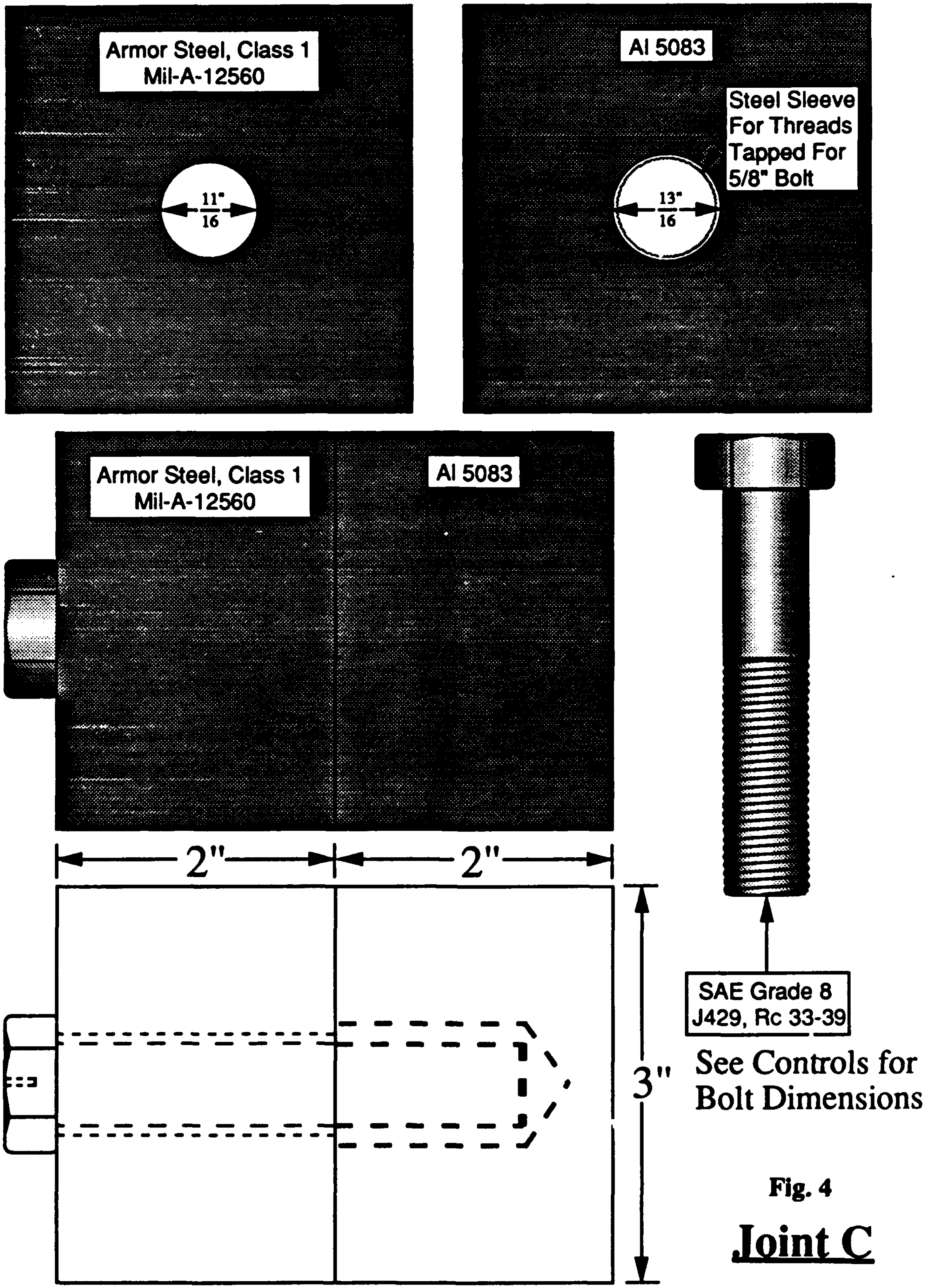

Armor Steel, Class 1
Mil-A-12560
11"/16
Al 5083
Steel Sleeve
For Threads
Tapped For
5/8" Bolt
13"/16
Armor Steel, Class 1
Mil-A-12560
Al 5083
2"
2"
3"
SAE Grade 8
J429, Rc 33-39
See Controls for
Bolt Dimensions

Fig. 4

Joint C

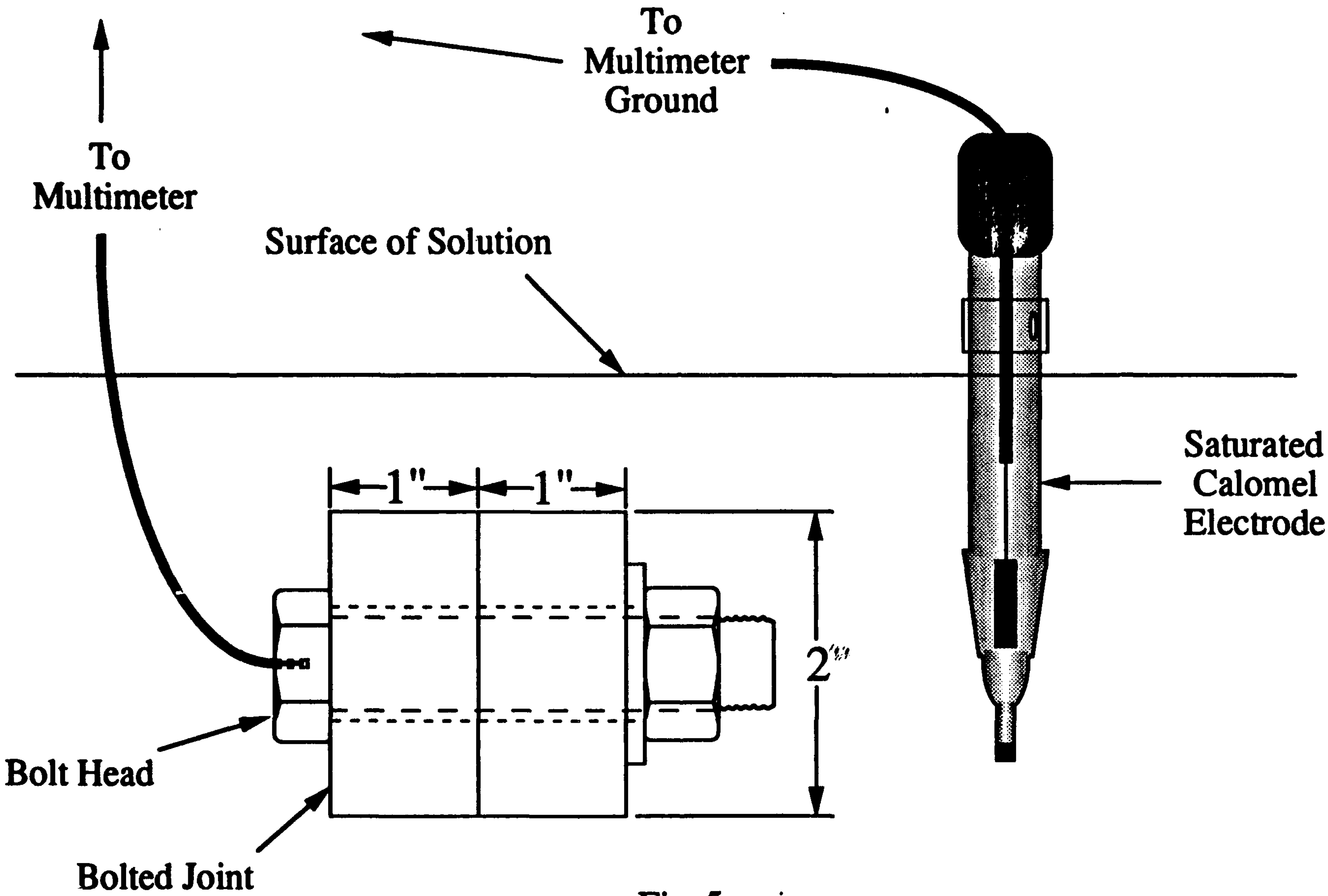
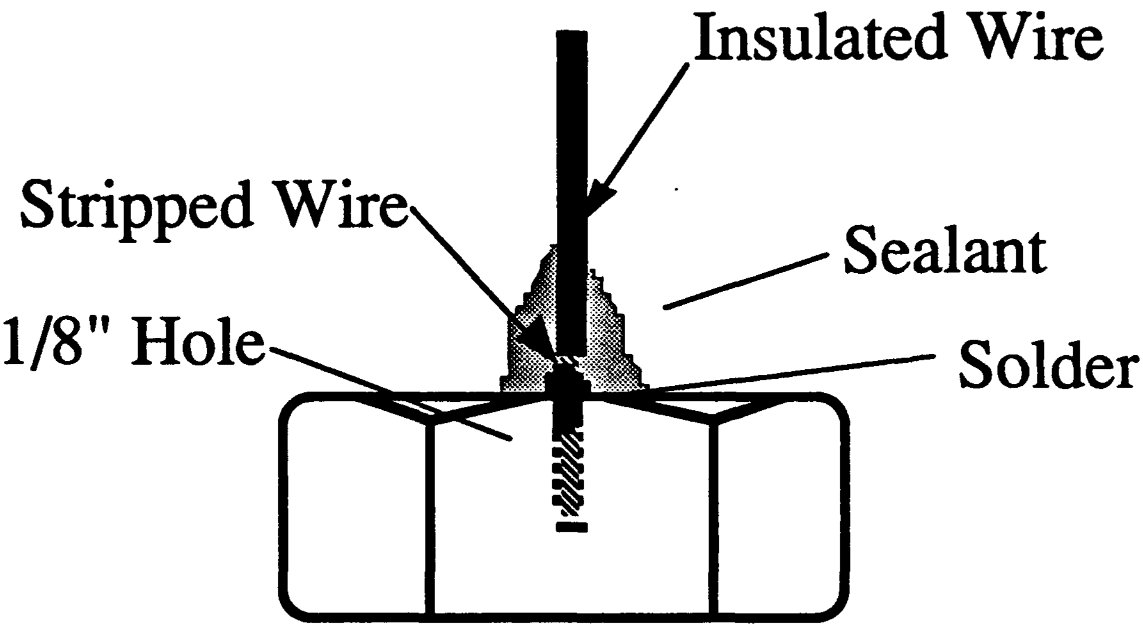


Fig. 5a

Potential Measurement of a Bolted Joint Immersed in 3.5 wt% Sodium Chloride Solution using a Saturated Calomel Electrode.

Fig. 5b

Close up of bolt head.



• A 1/8" hole was drilled in the center of the head of the bolt. The hole was approximately 3/8" deep.

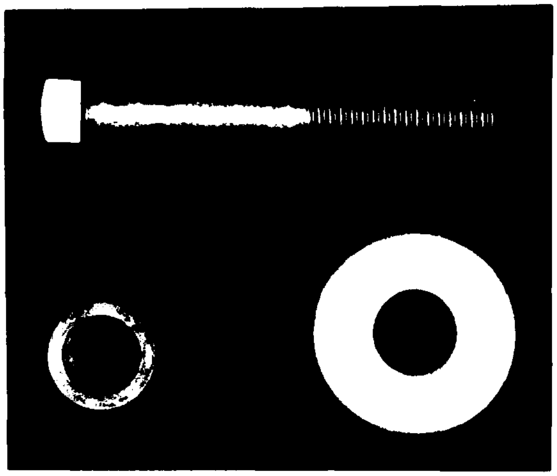
• The stripped end of a insulated tin-copper wire, 22 AWG, approximately 2 feet long, was soldered into the hole in the head of the bolt.

• The stripped wire and the region of the bolt which was damaged in this process was sealed with a non-corrosive silicone rubber.

• The joints were then assembled and immersed in the circulating baths with the wires leading from the bath and secured in a dry place.

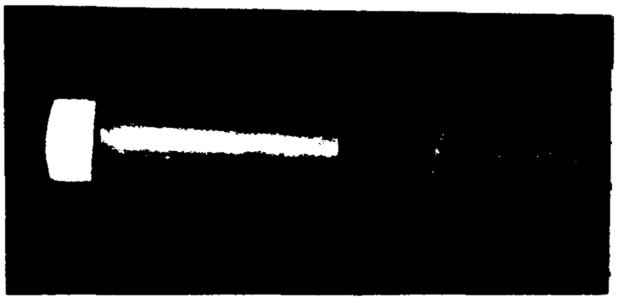
• The potential was measured with a saturated calomel electrode using a Keithley 179A TRMS multimeter.

Cd Control - Saltspray



Initial

Initial



96 Hours

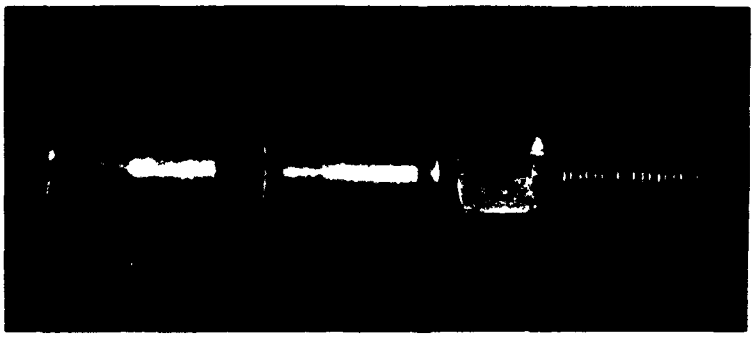


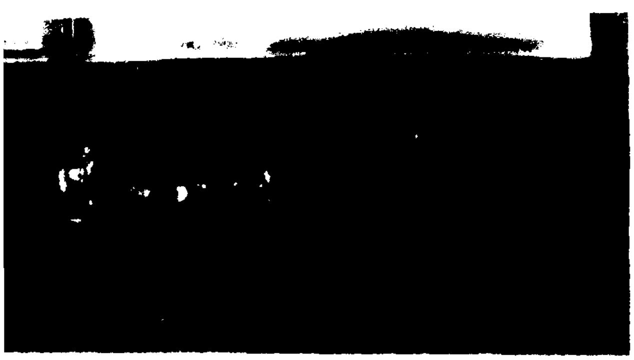
Figure 6

312 Hours

Zn Olive Drab Control - Saltspray

Initial

Initial

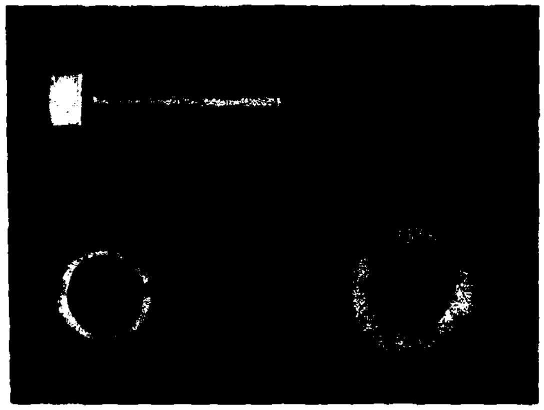


96 Hours

312 Hours

Figure 7

Zn-Ni Control - Saltspray



Initial

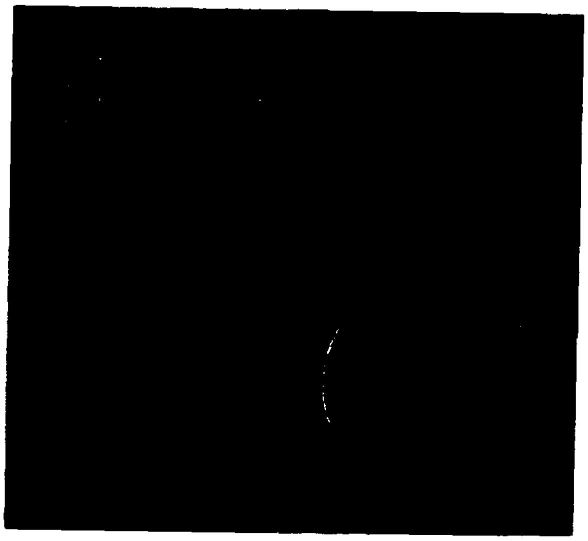
Initial

96 Hours

312 Hours

Figure 8

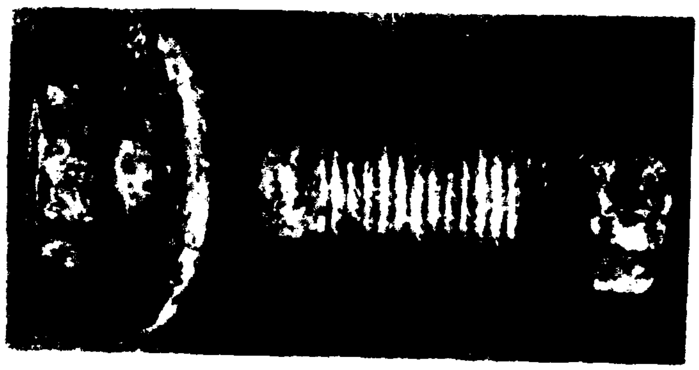
Zn-Co Control - Saltspray



Initial

Initial

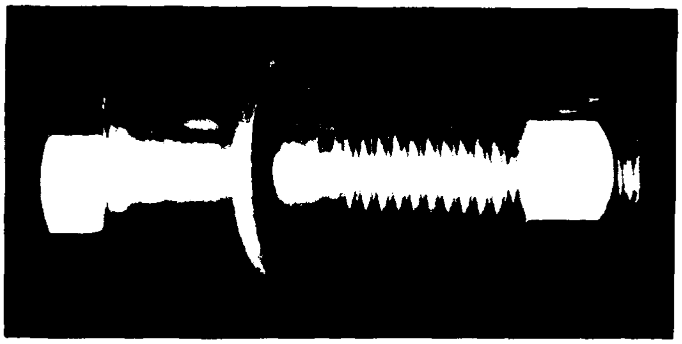
96 Hours



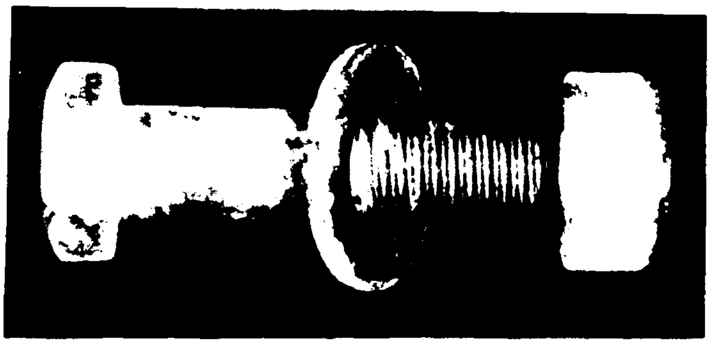
312 Hours

Figure 9

Sn-Zn Control - Saltspray



Initial



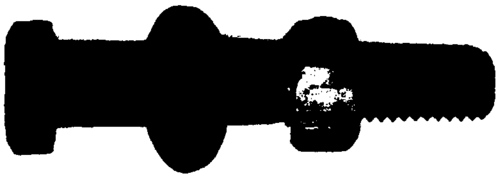
312 Hours

Figure 10

Modified Phosphate Control - Saltspray

Initial

Initial



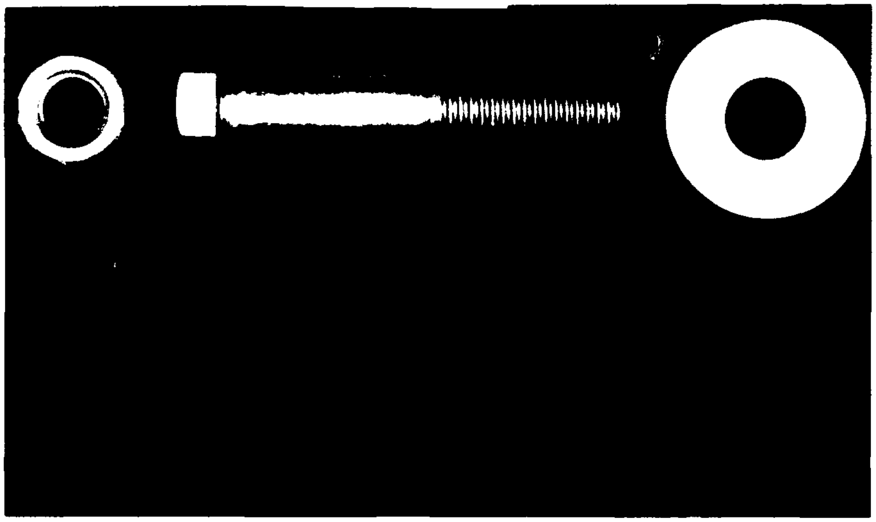
48 Hours

96 Hours

312 Hours

Figure 11

Cd (BWN) Joint A - Saltspray



Initial

Initial

96 Hours

312 Hours

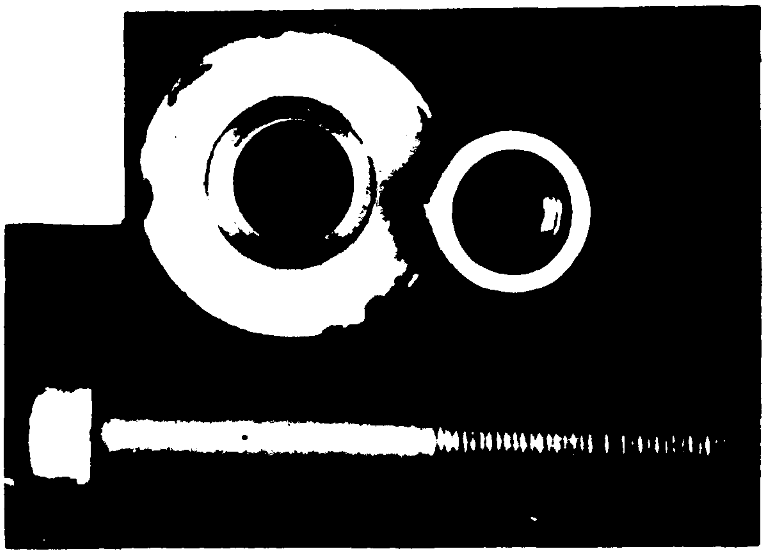
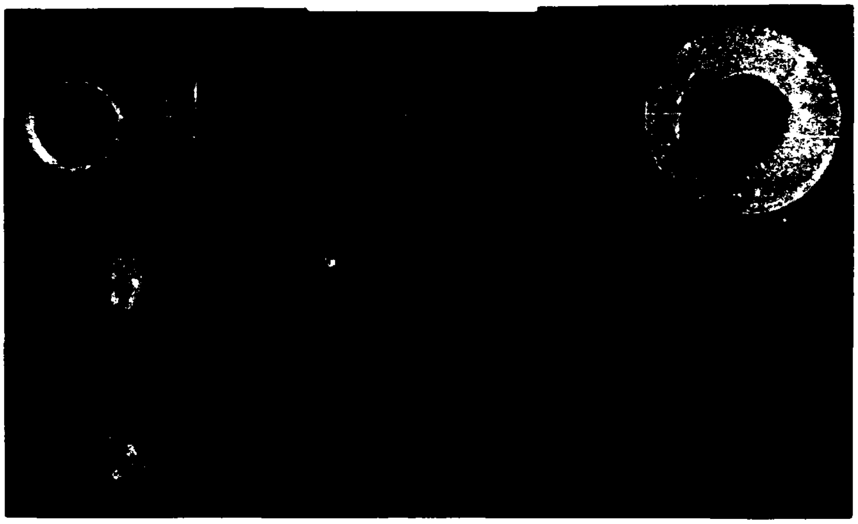


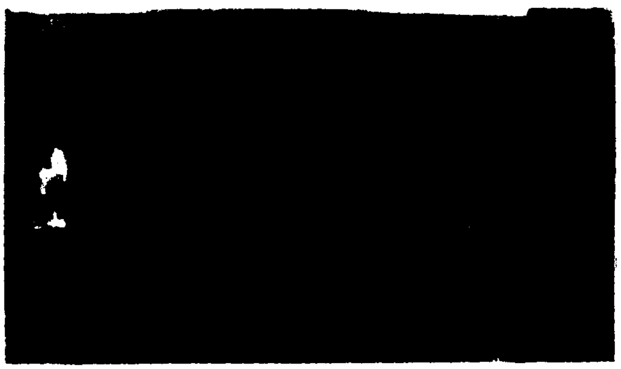
Figure 12 312 Hours

Zn Olive Drab (BWN) Joint A - Saltspray

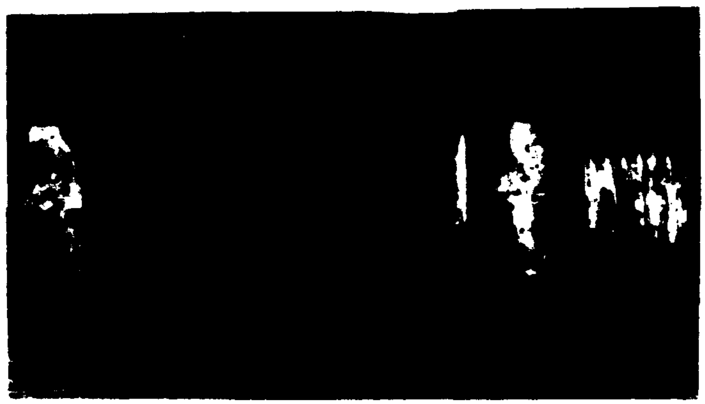


Initial

Initial

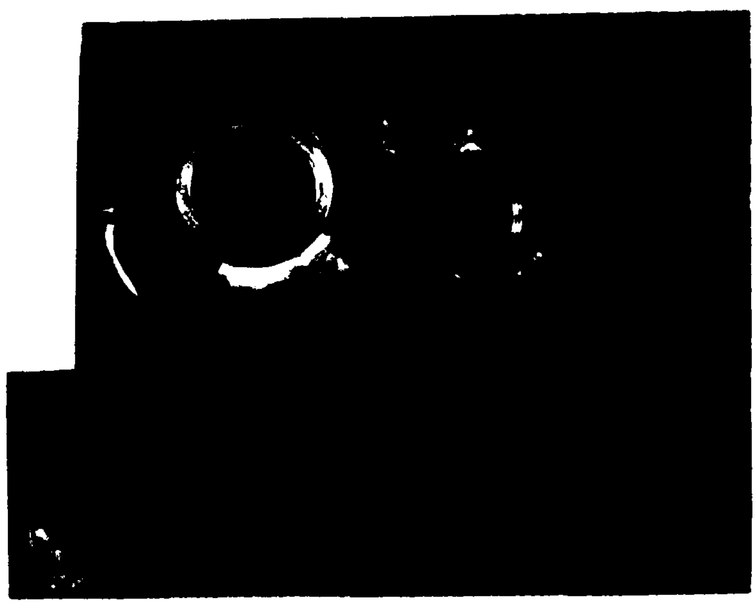


96 Hours



312 Hours

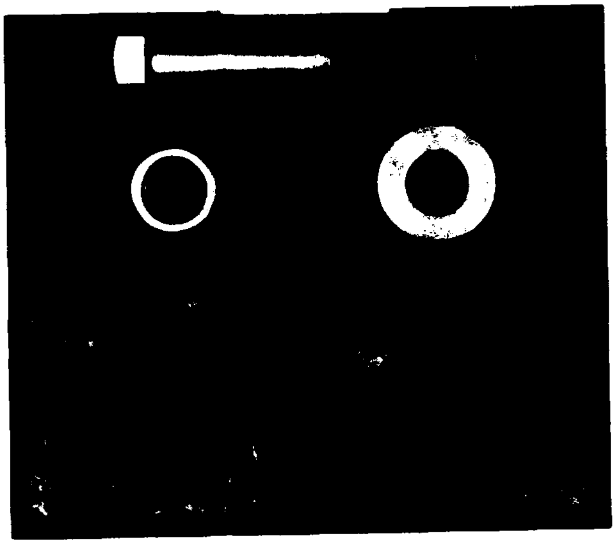
312 Hours



312 Hours

Figure 13

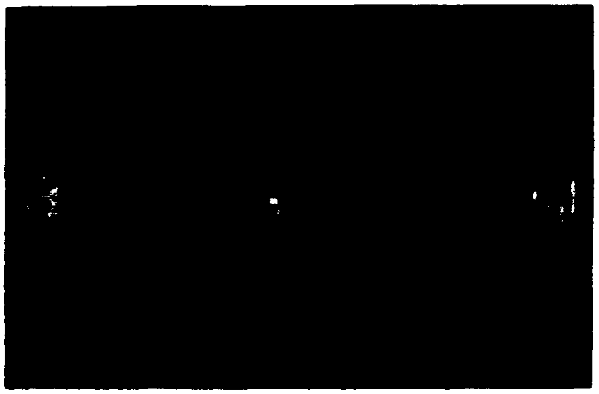
Zn-Ni (BWN) Joint A - Saltspray



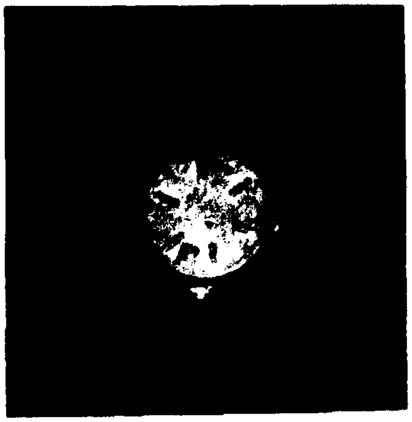
Initial

Initial

96 Hours



312 Hours



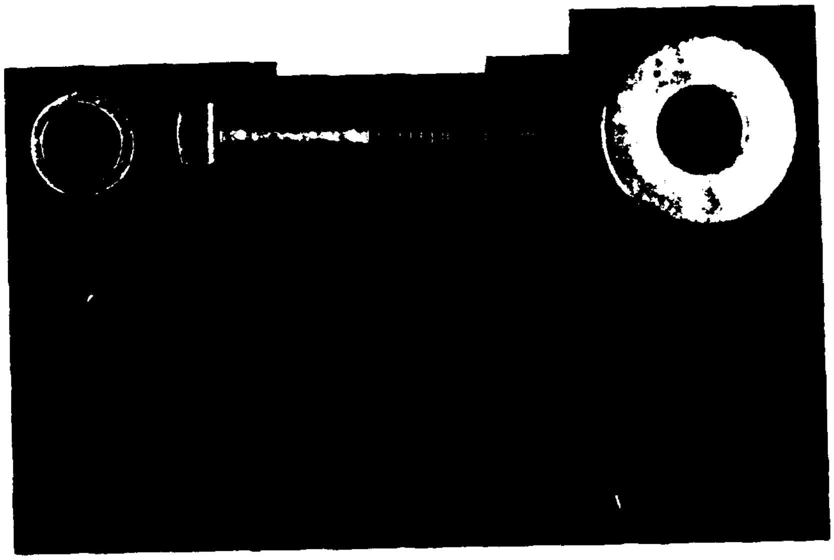
312 Hours

312 Hours

Figure 14

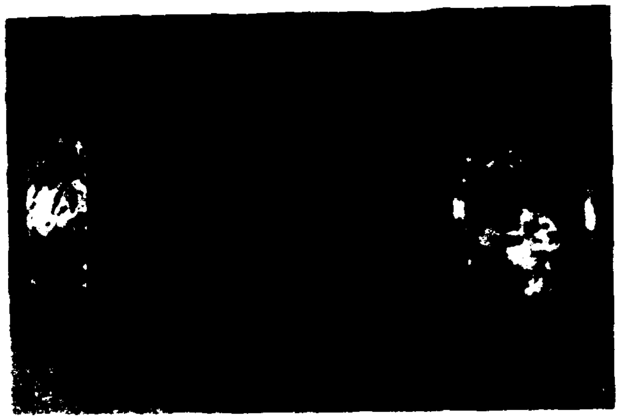
Zn-Co (BWN) Joint A - Saltspray

Initial



Initial

96 Hours



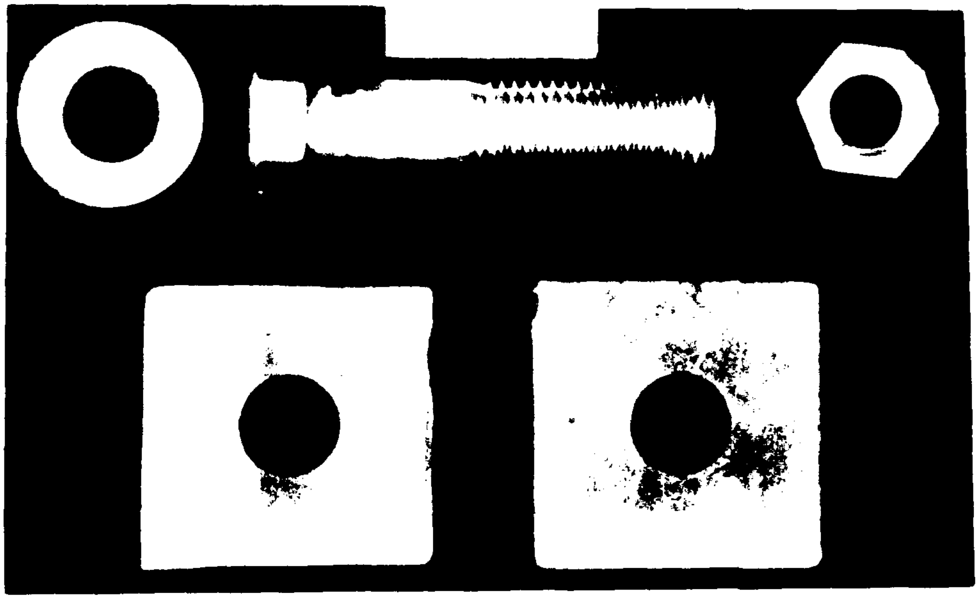
312 Hours

312 Hours

312 Hours

Figure 15

Sn-Zn (BWN) Joint A - Saltspray



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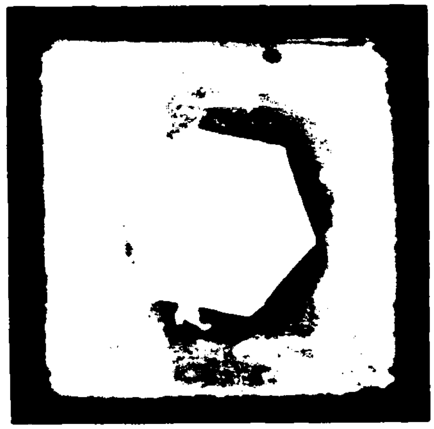
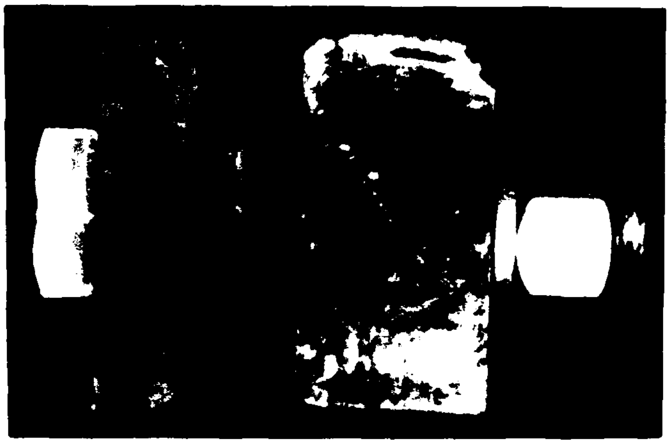


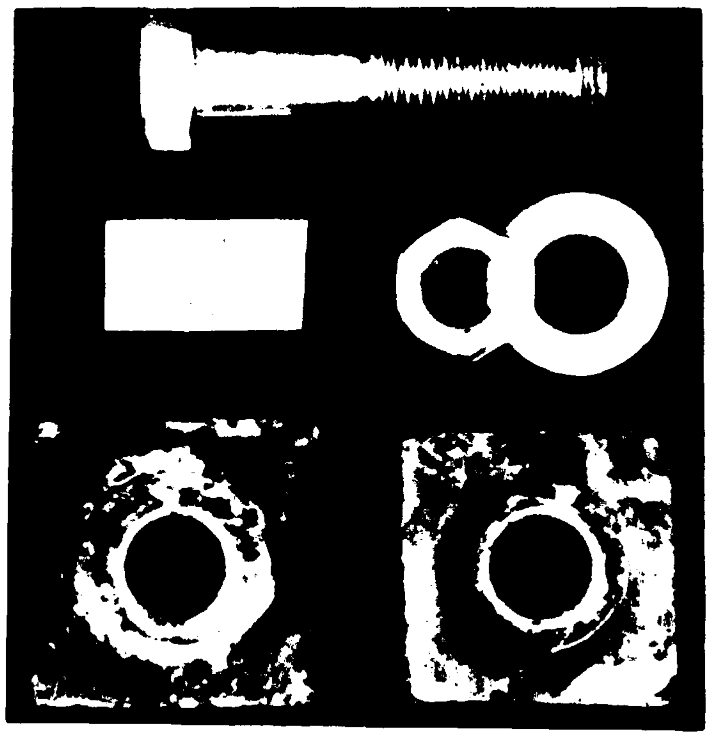
312 Hours

312 Hours



Initial

312 Hours

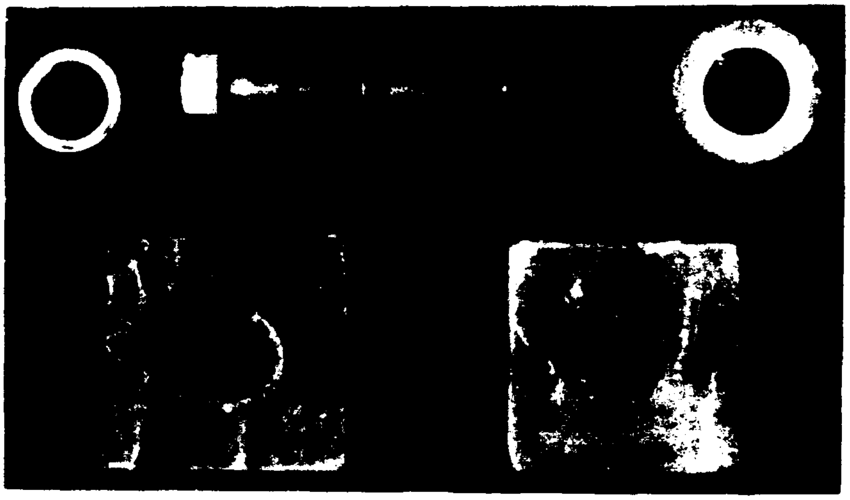


312 Hours

Figure 16

Modified Phosphate (BWN) Joint A - Saltspray

Initial



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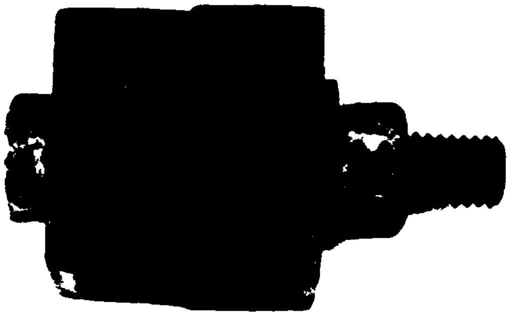


48 Hours

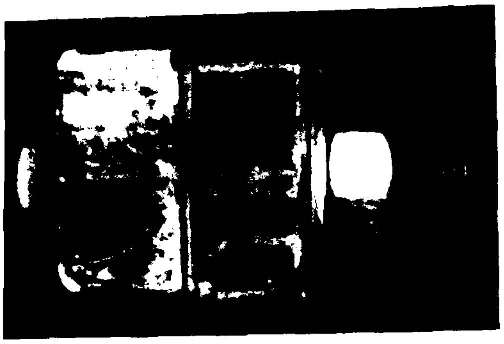
96 Hours

312 Hours

312 Hours

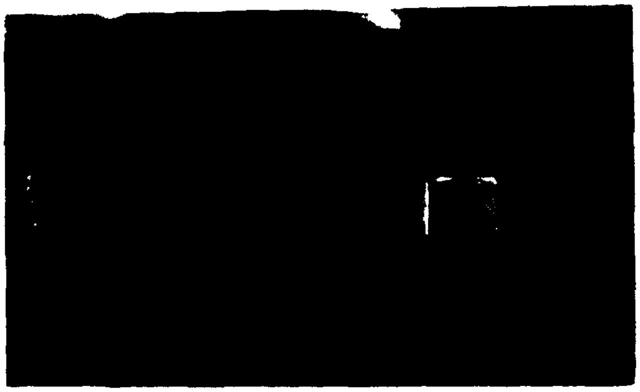
Figure 17

Zn Olive Drab with Cd, Joint A - Saltspray

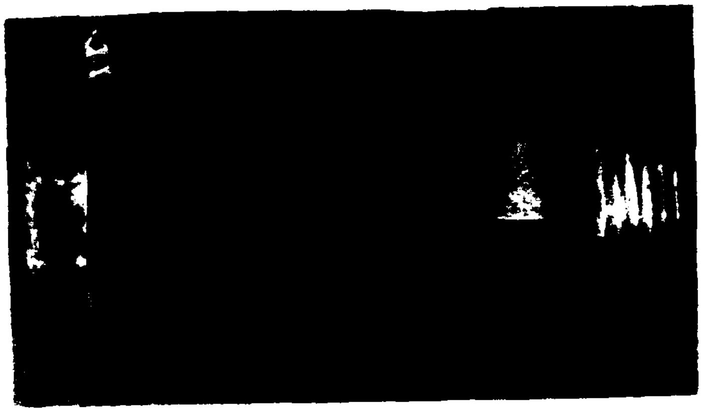


Initial

Initial

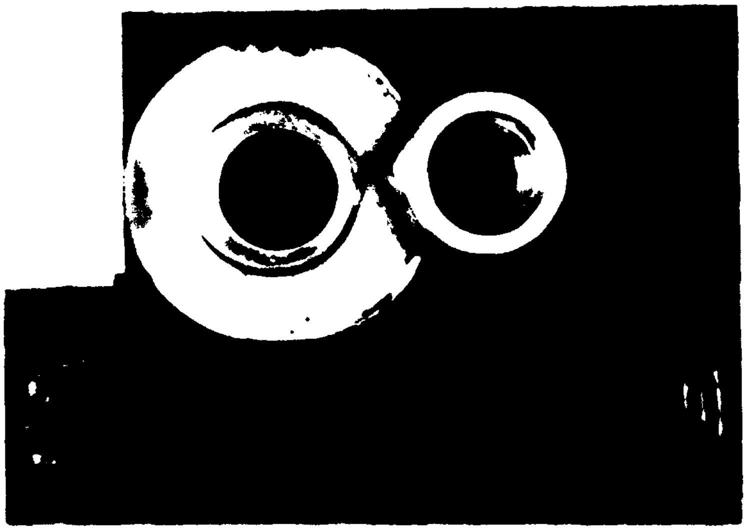


96 Hours



312 Hours

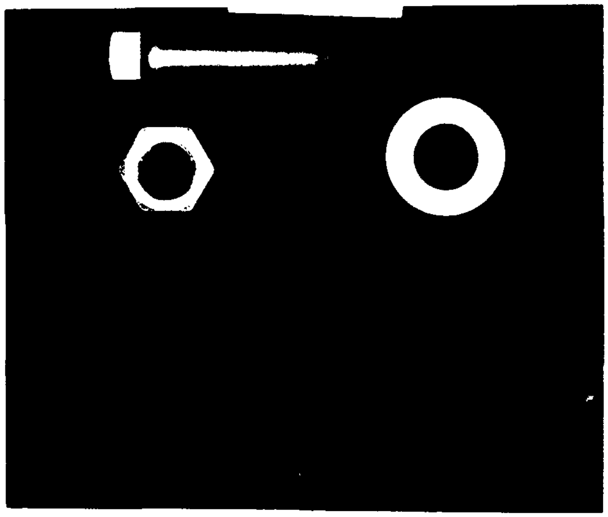
312 Hours



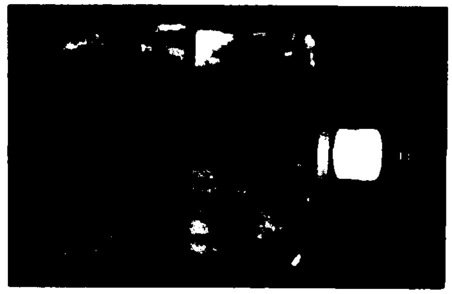
312 Hours

Figure 18

Zn-Ni with Cd, Joint A - Saltspray



Initial



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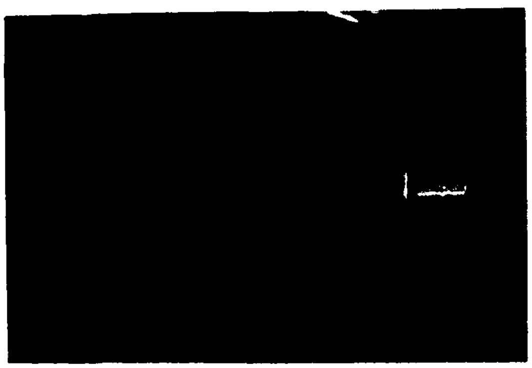
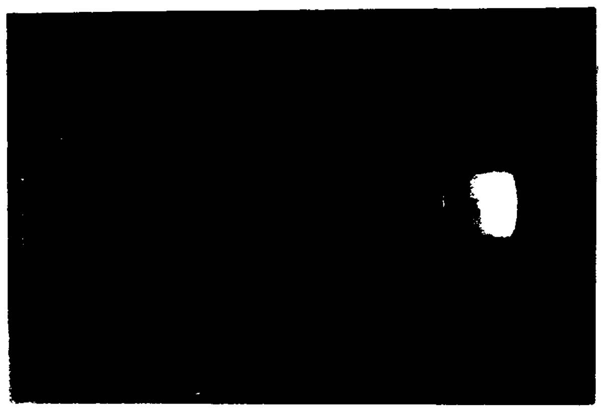
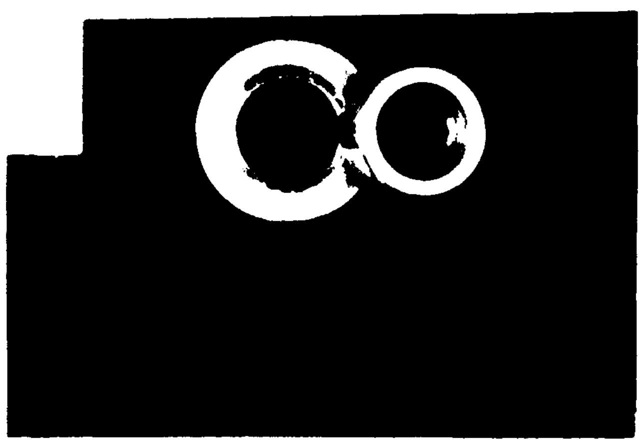


96 Hours



312 Hours

312 Hours

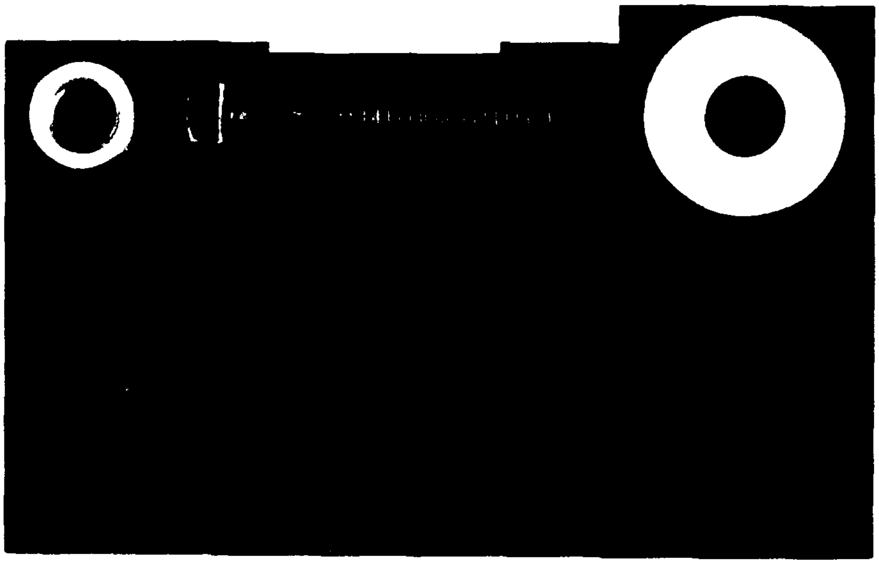


312 Hours

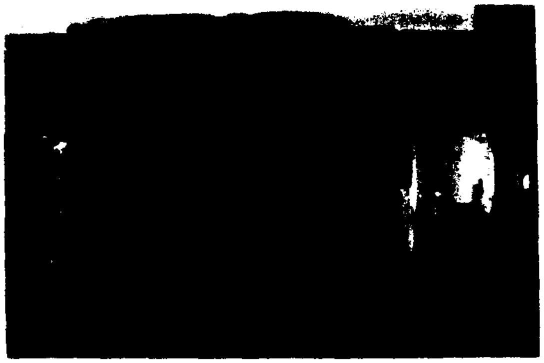
Figure 19

Zn-Co with Cd, Joint A - Saltspray

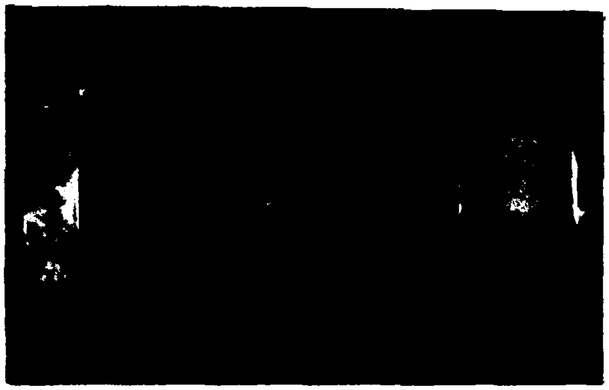
Initial



Initial

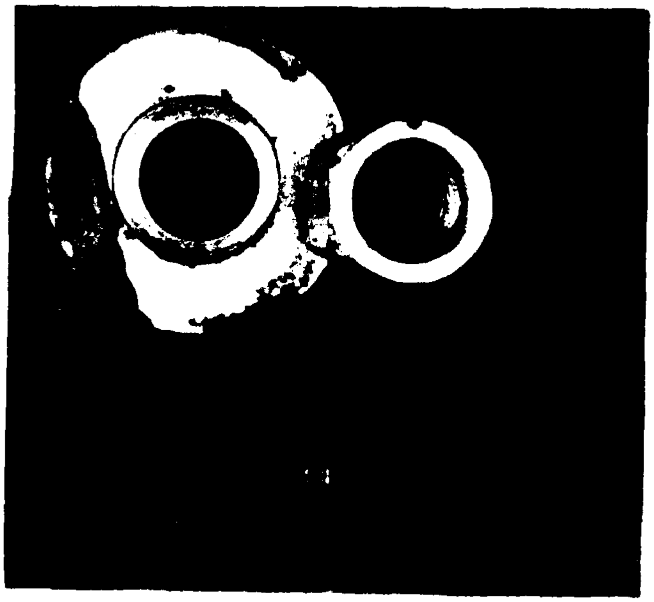


96 Hours



312 Hours

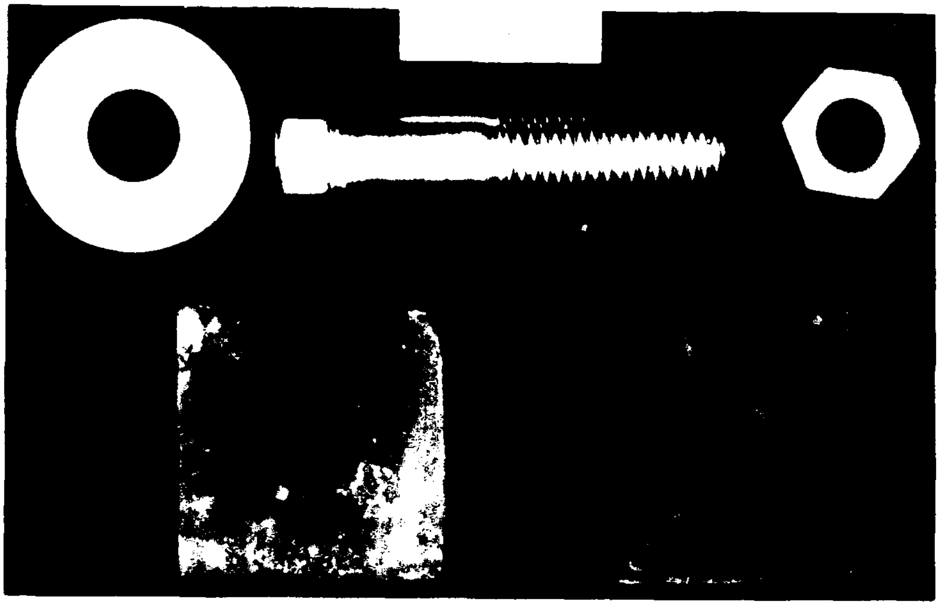
312 Hours



312 Hours

Figure 20

Sn-Zn with Cd, Joint A - Saltspray

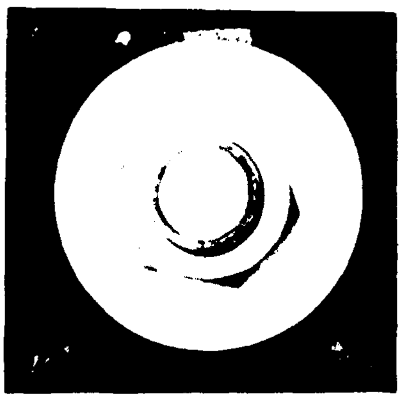


Initial

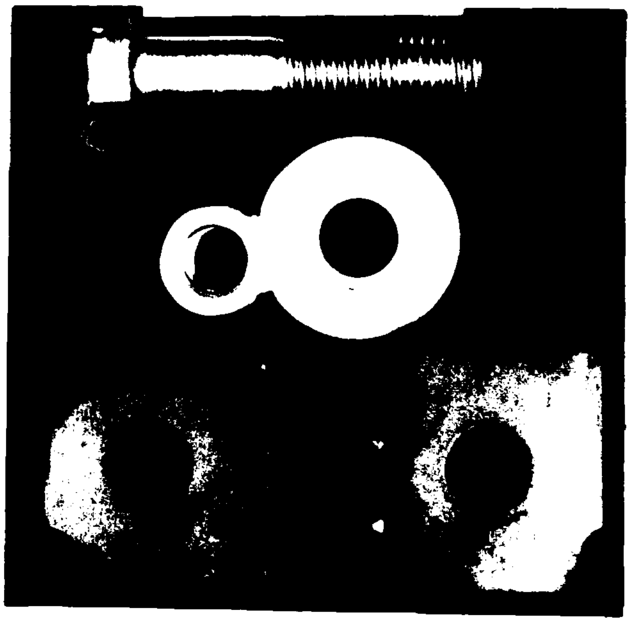
Initial

312 Hours

312 Hours



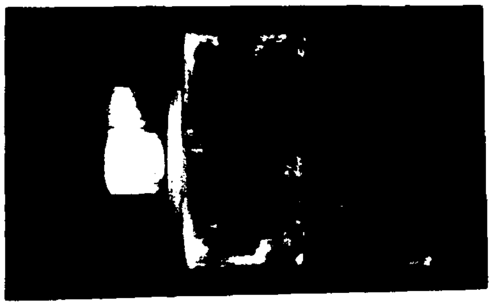
312 Hours



312 Hours

Figure 21

Modified Phosphate with Cd, Joint A - Saltspray



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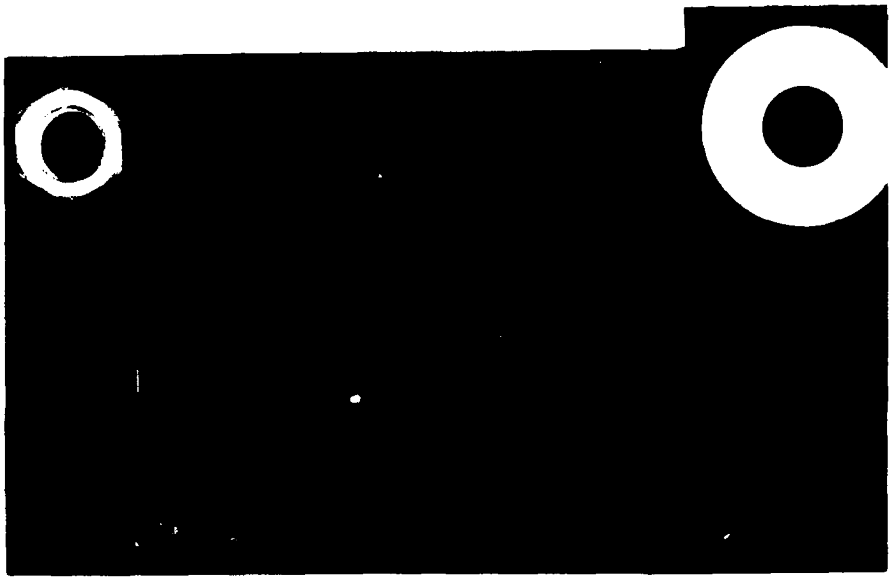
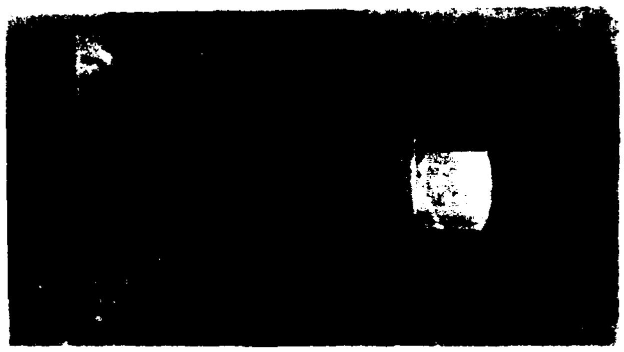


Initial

48 Hours

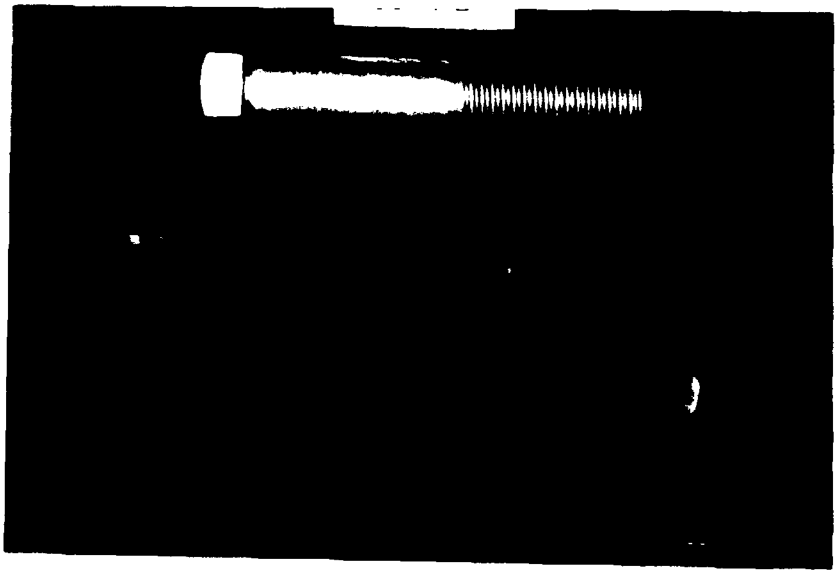


96 Hours

312 Hours

Figure 22 312 Hours

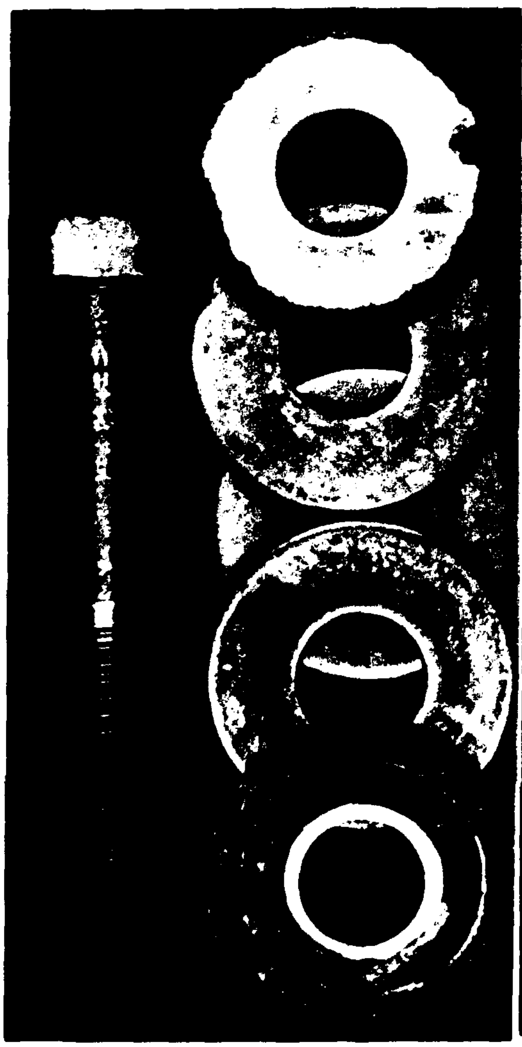
Cd Joint B - Saltspray



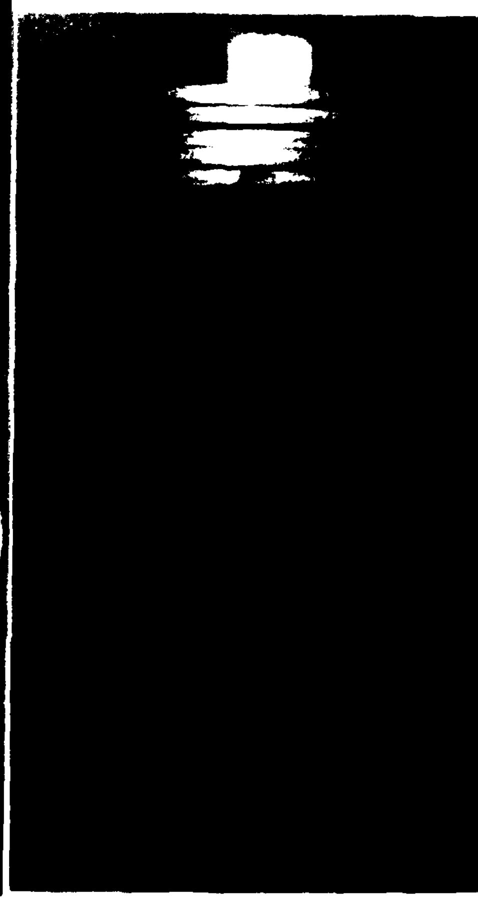
Initial

96 Hours

312 Hours



312 Hours

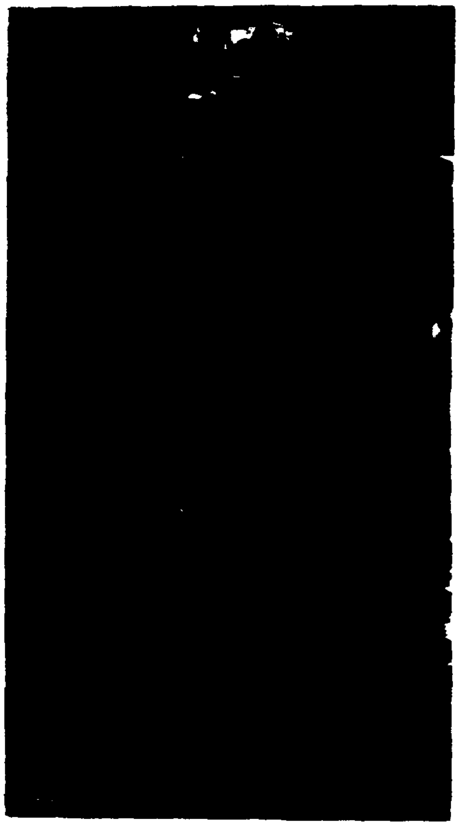


312 Hours

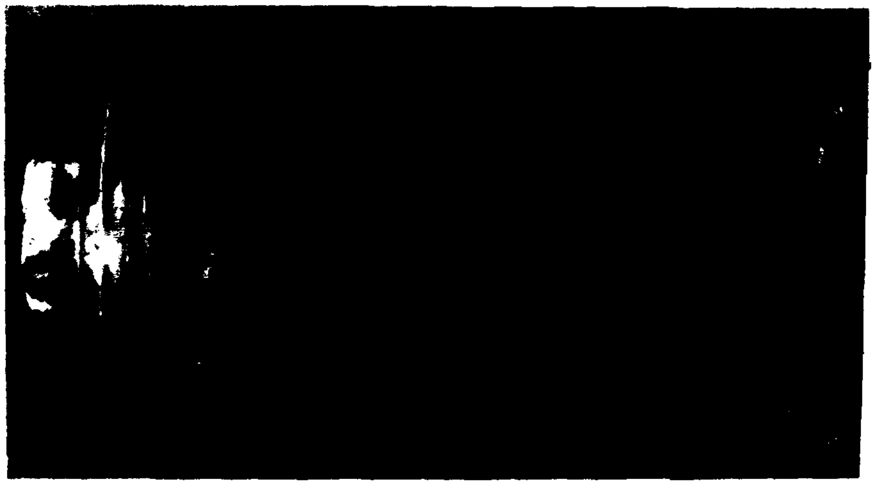
Figure 23

Zn Olive Drab Joint B - Saltspray

Initial

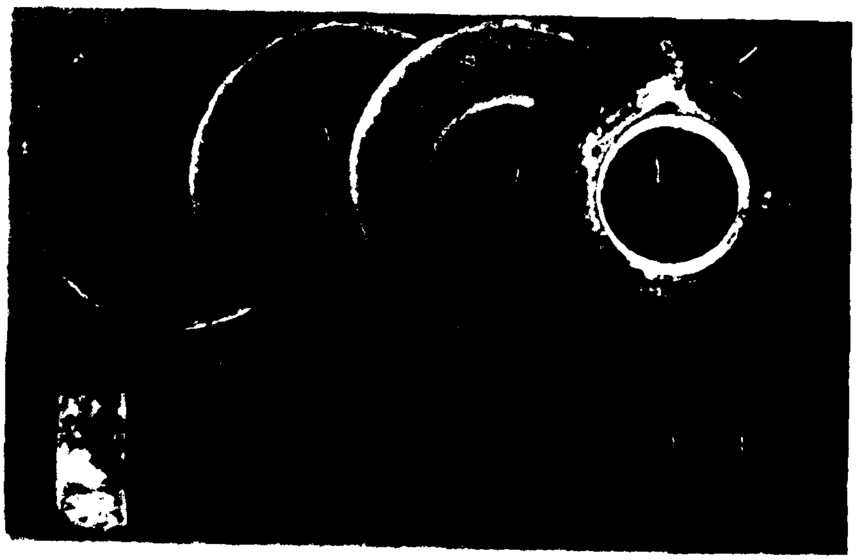


96 Hours



312 Hours

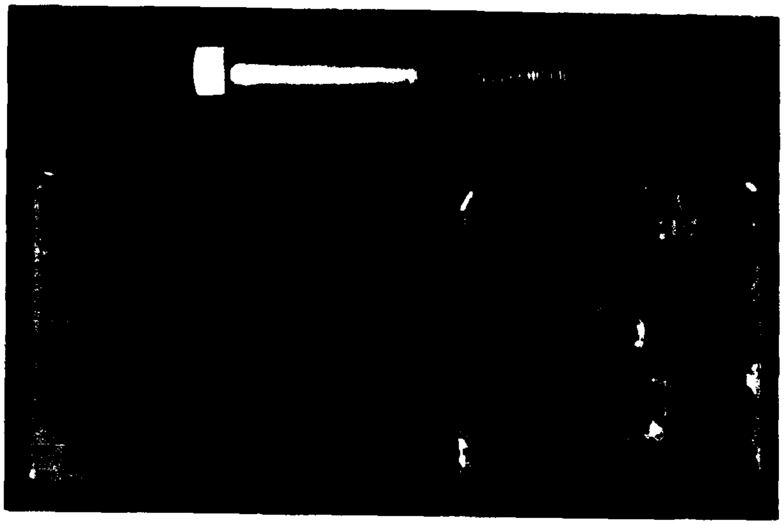
312 Hours



312 Hours

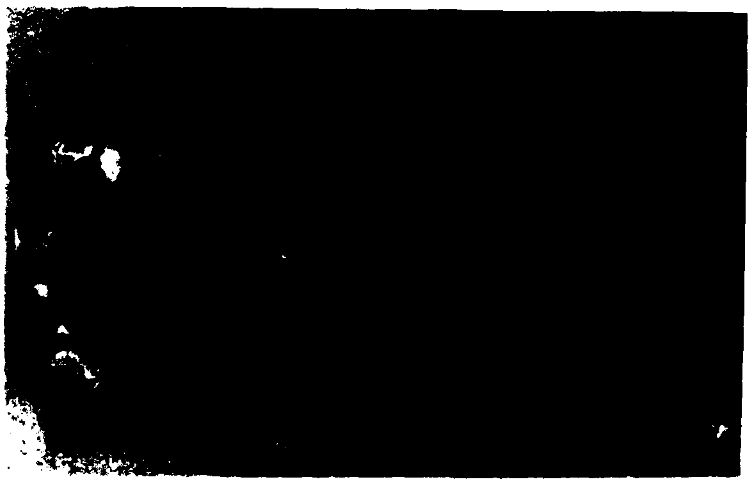
Figure 24

Zn-Ni Joint B - Saltspray



Initial

96 Hours



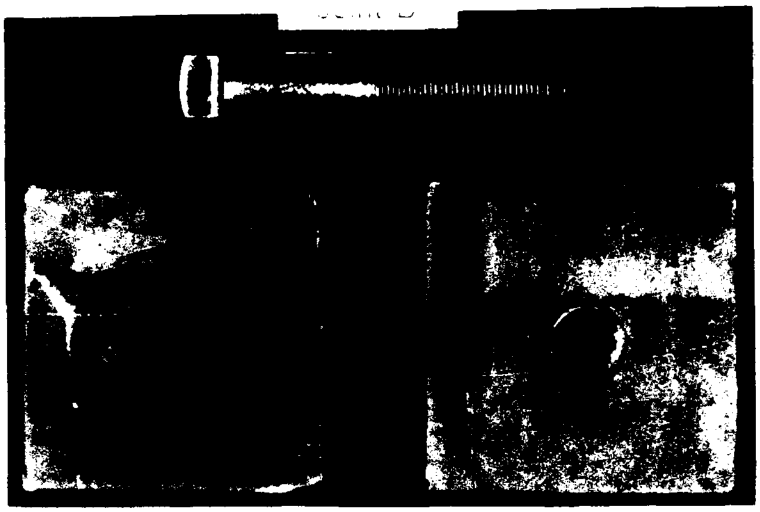
312 Hours

312 Hours

312 Hours

Figure 25

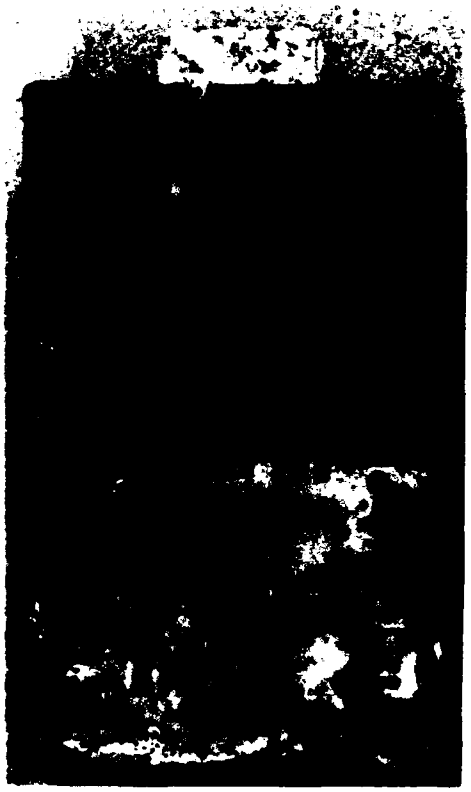
Zn-Co Joint B - Saltspray



Initial

96 Hours

312 Hours

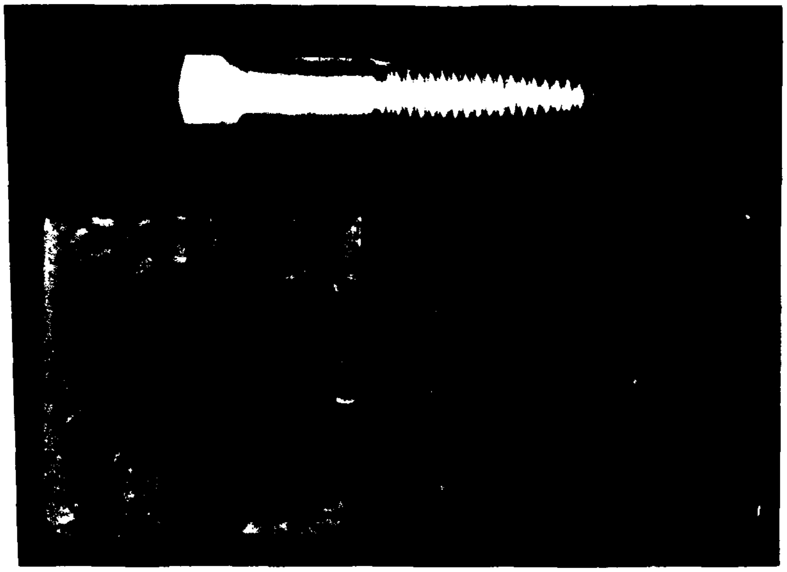


312 Hours

312 Hours

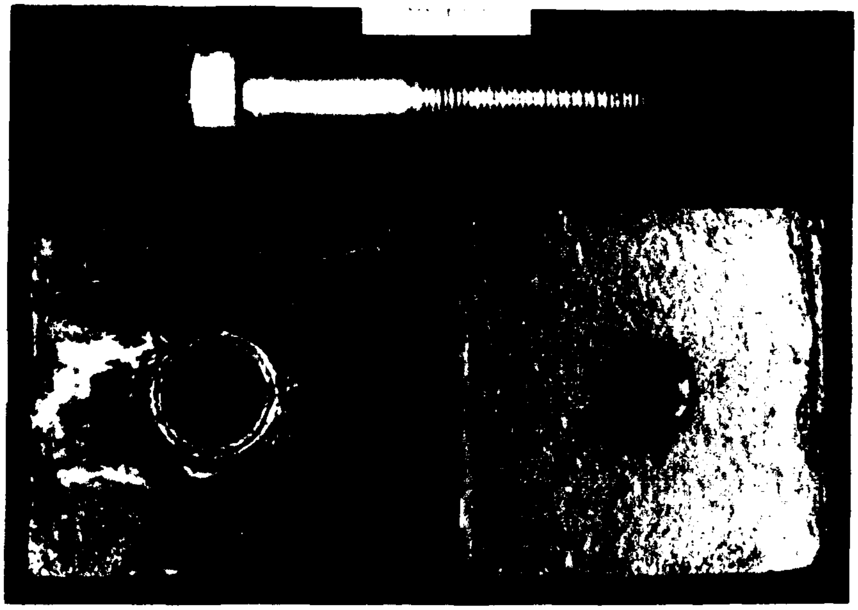
Figure 26

Sn-Zn Joint B - Saltspray



Initial

312 Hours

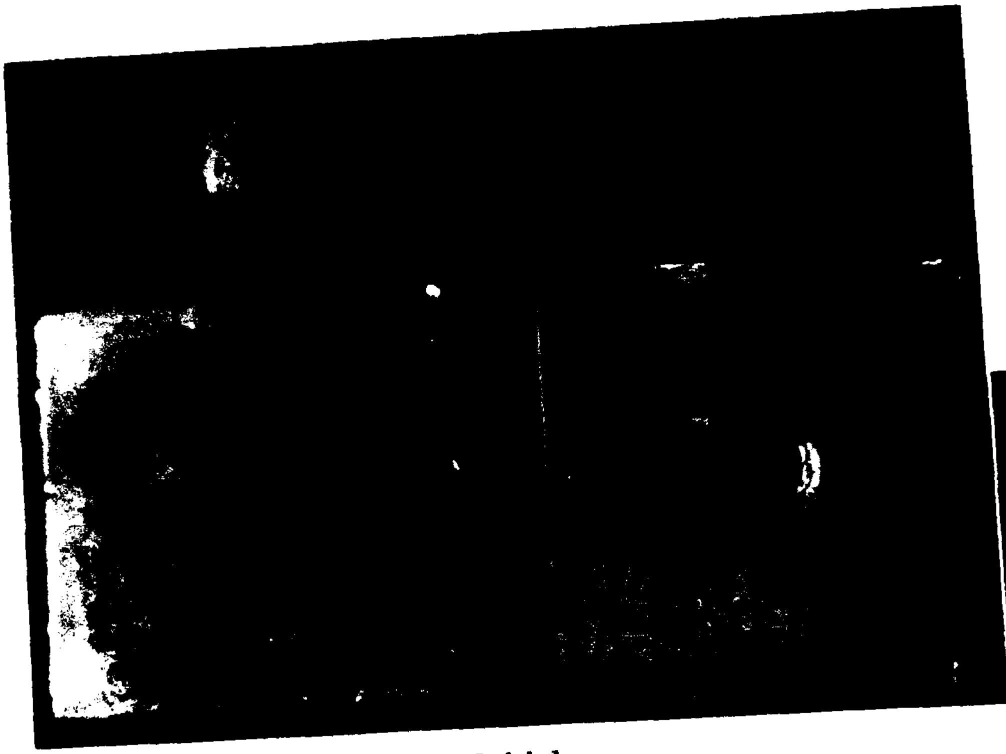


312 Hours

312 Hours

Figure 27

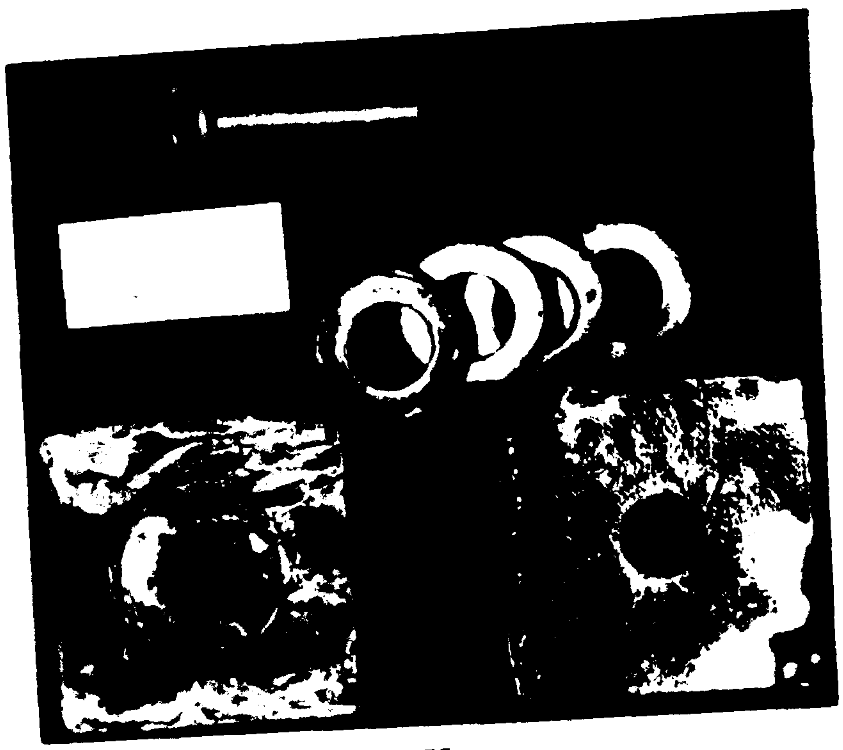
Modified Phosphate Joint B - Saltspray



Initial

312 Hours

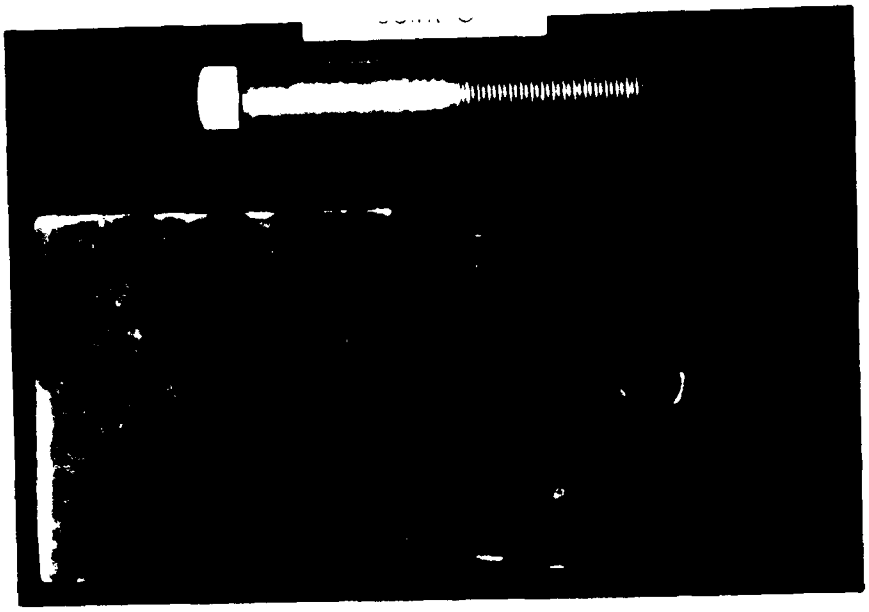
312 Hours



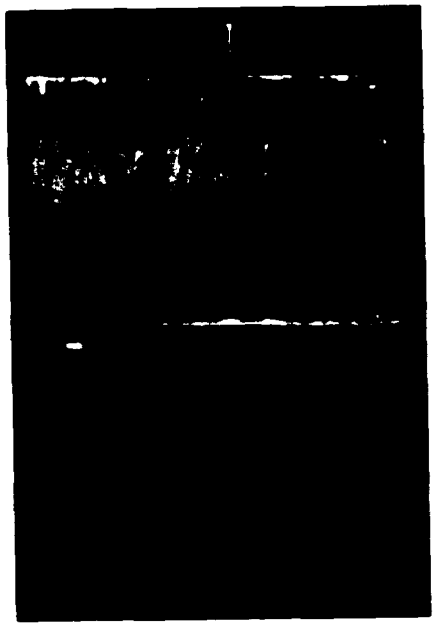
312 Hours

Figure 28

Cd Joint C - Saltspray

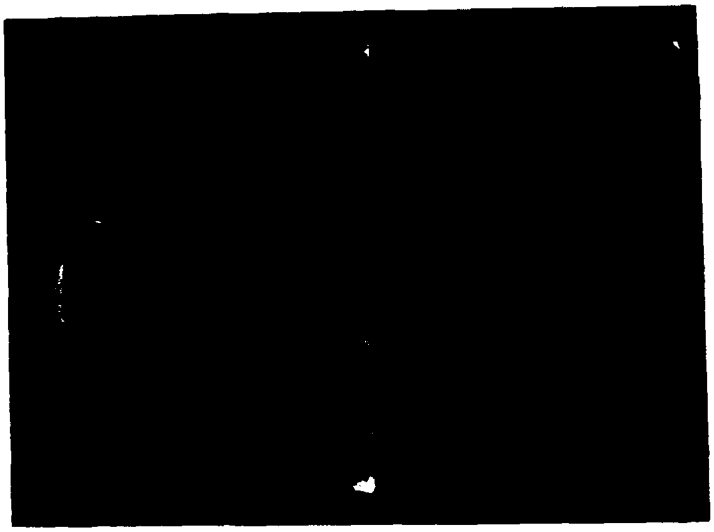


Initial

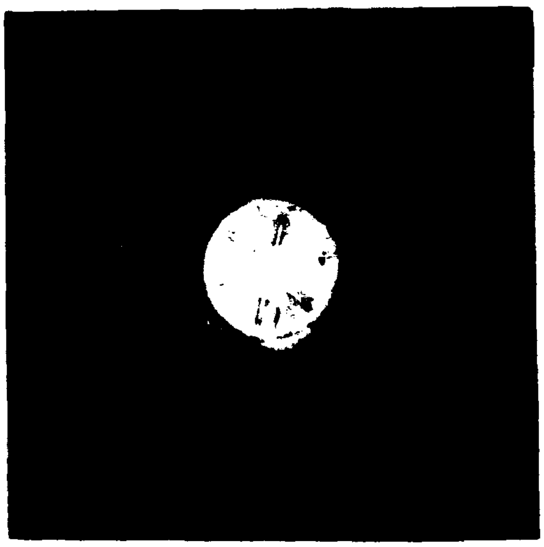


Initial

96 Hours



312 Hours



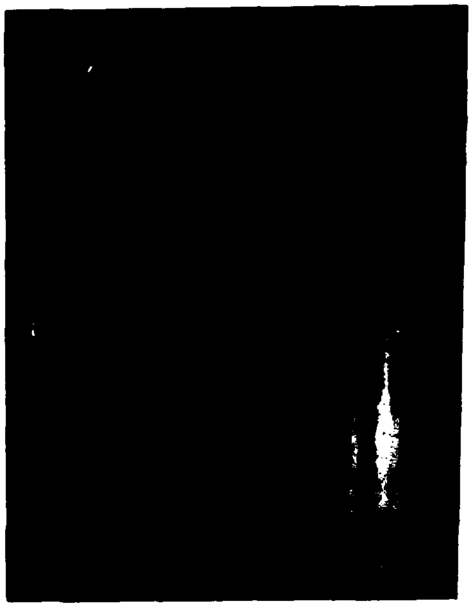
312 Hours

312 Hours

Figure 29

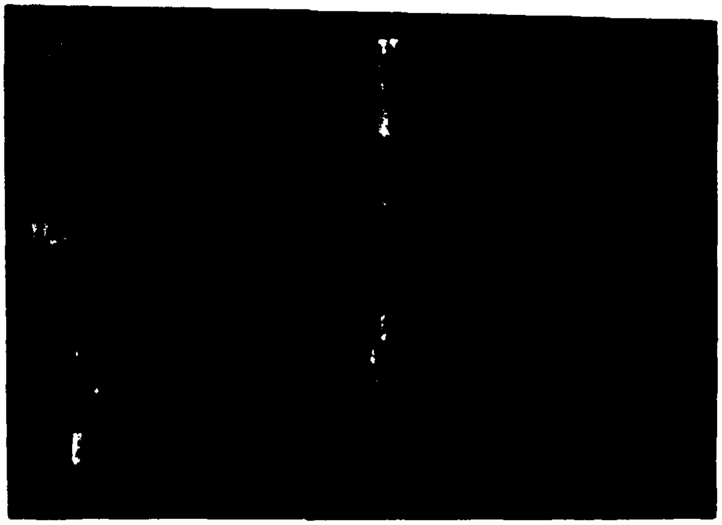
Zn Olive Drab Joint C - Saltspray

Initial



Initial

96 Hours



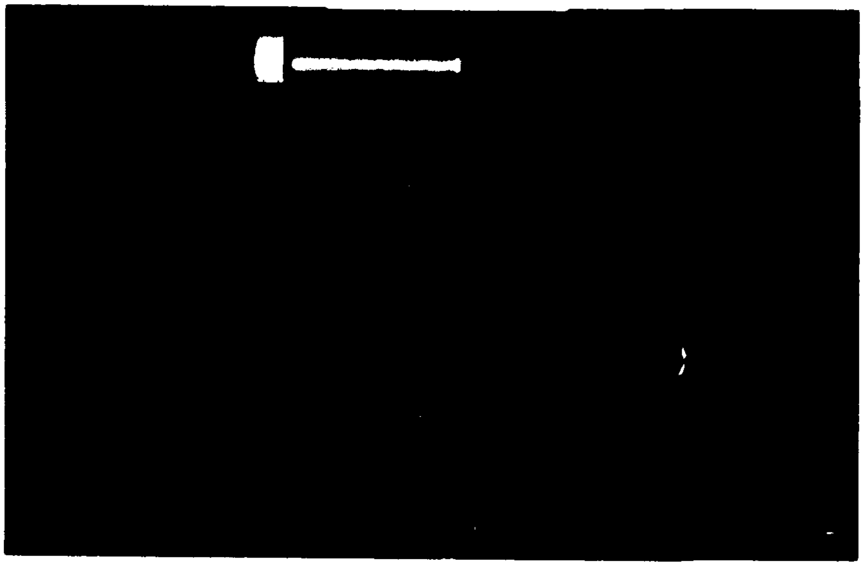
312 Hours

312 Hours

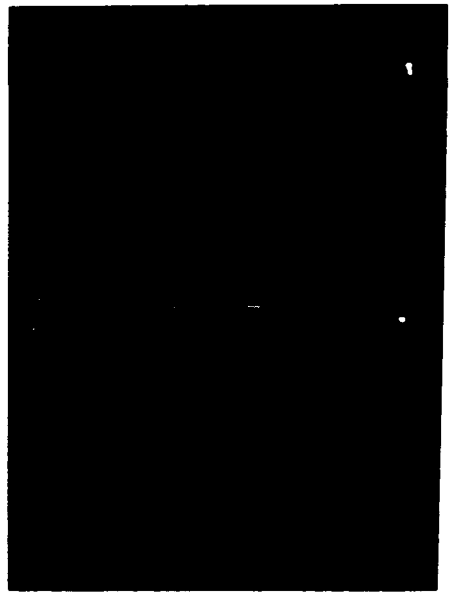
312 Hours

Figure 30

Zn-Ni Joint C - Saltspray

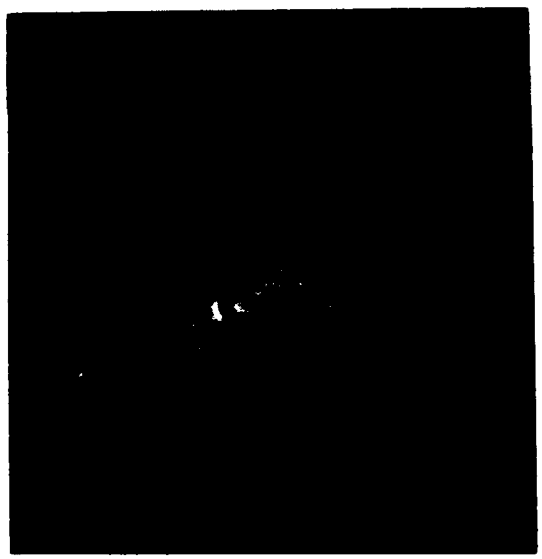


Initial



Initial

96 Hours



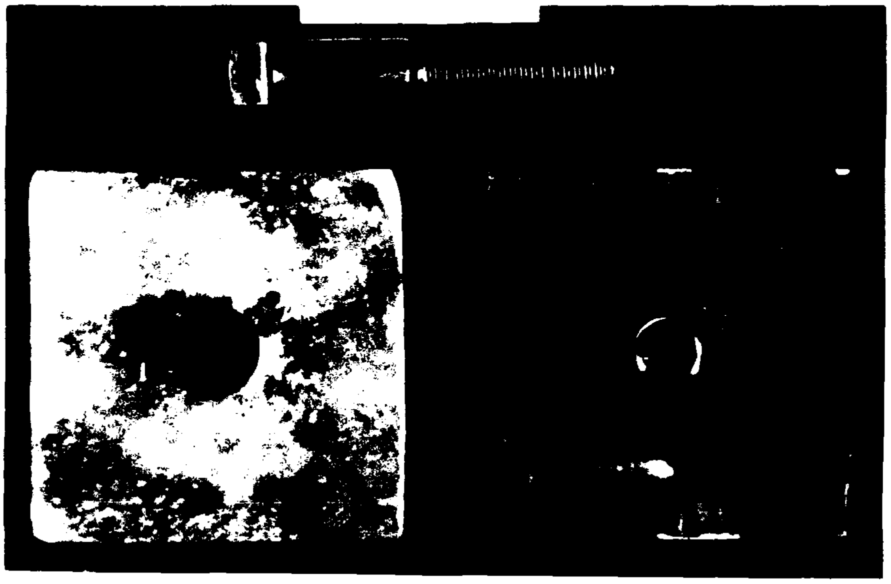
312 Hours

312 Hours

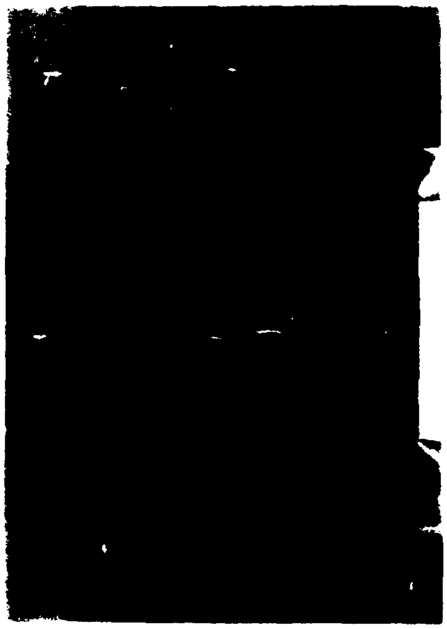
312 Hours

Figure 31

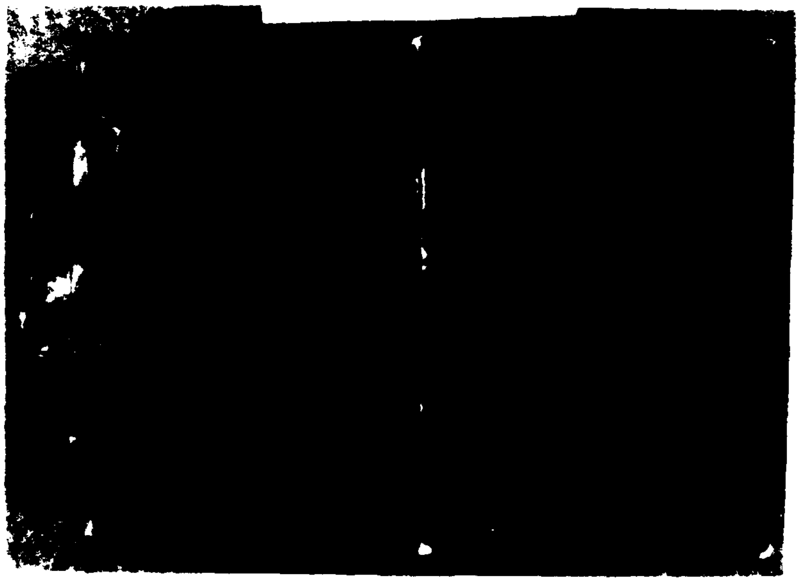
Zn-Co Joint C - Saltspray



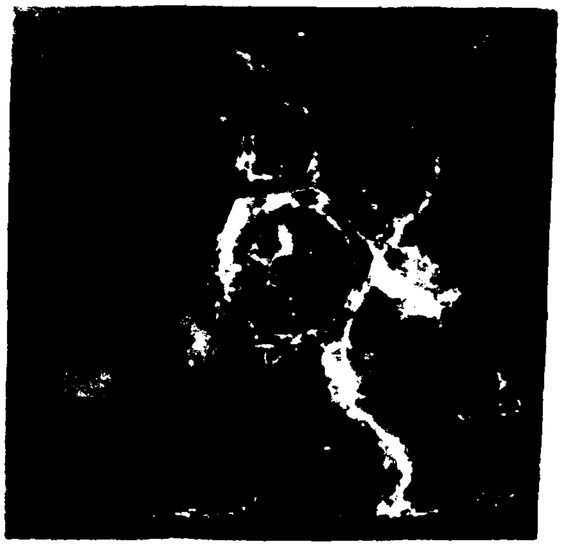
Initial



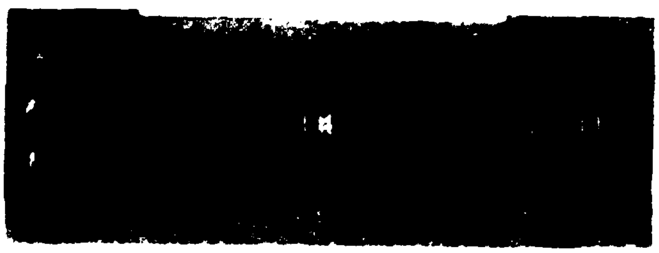
96 Hours



312 Hours



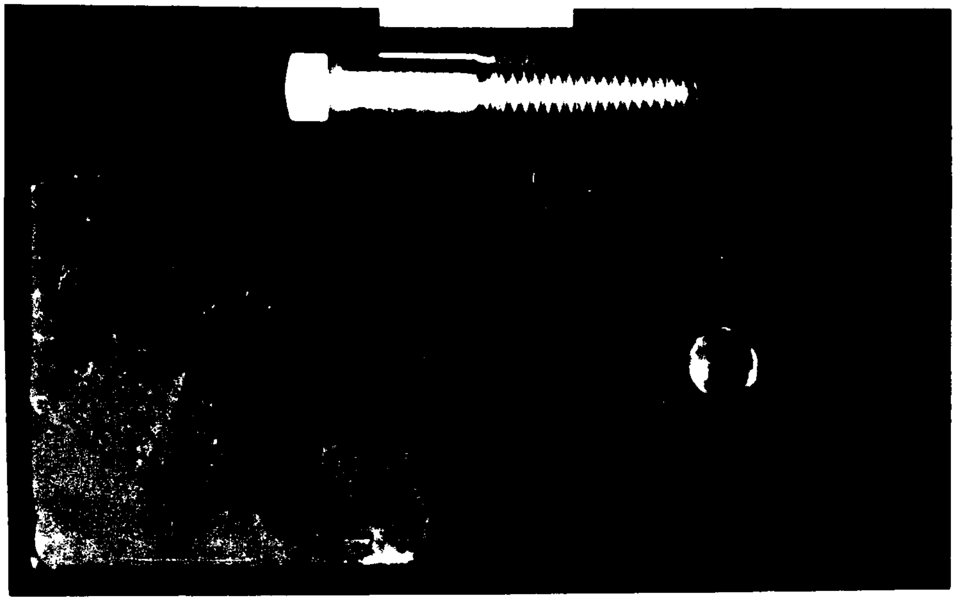
312 Hours



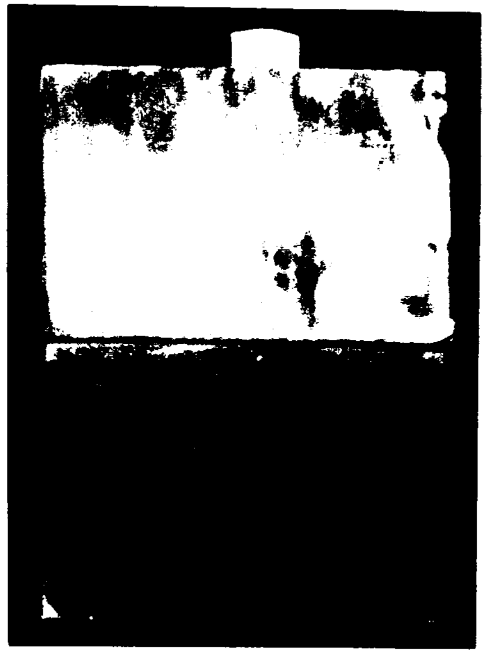
312 Hours

Figure 32

Sn-Zn Joint C - Saltspray



Initial



Initial

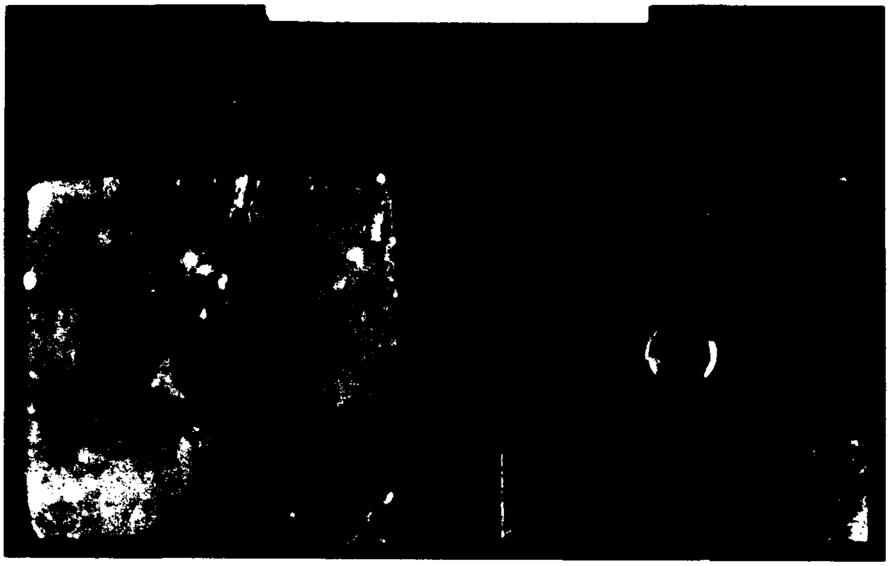
312 Hours

312 Hours

312 Hours

Figure 33

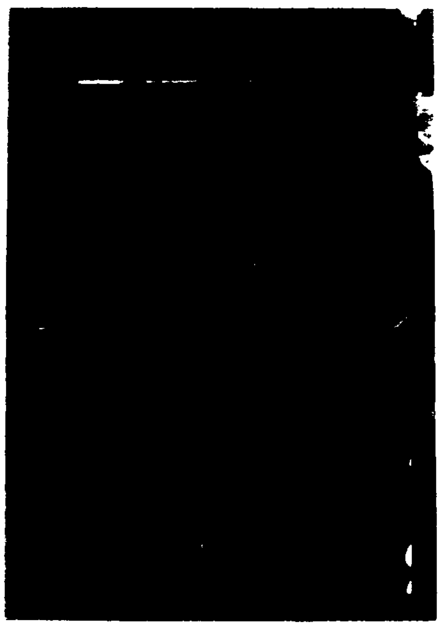
Modified Phosphate Joint C - Saltspray



Initial

48 Hours

48 Hours



96 Hours

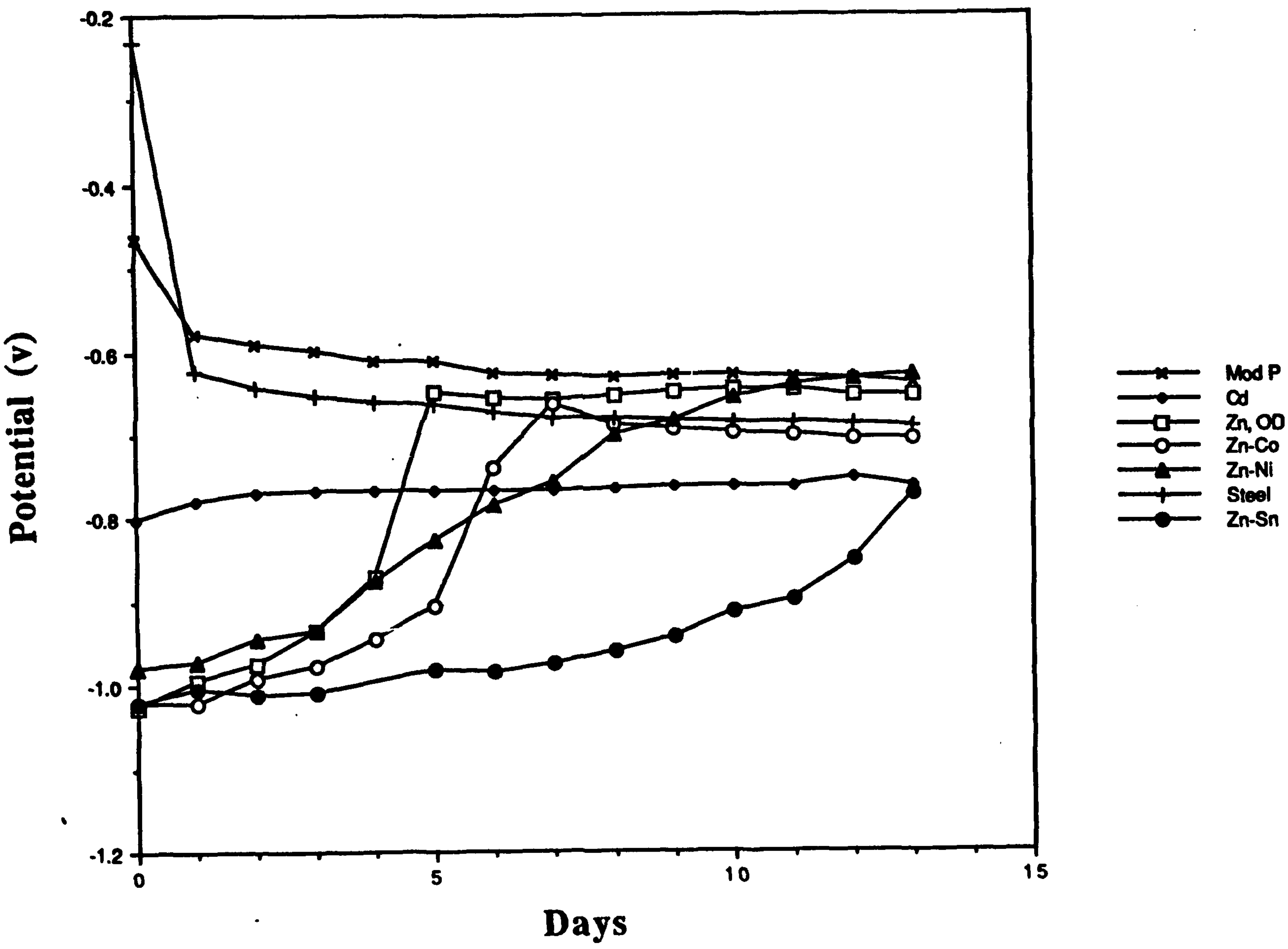
312 Hours

312 Hours

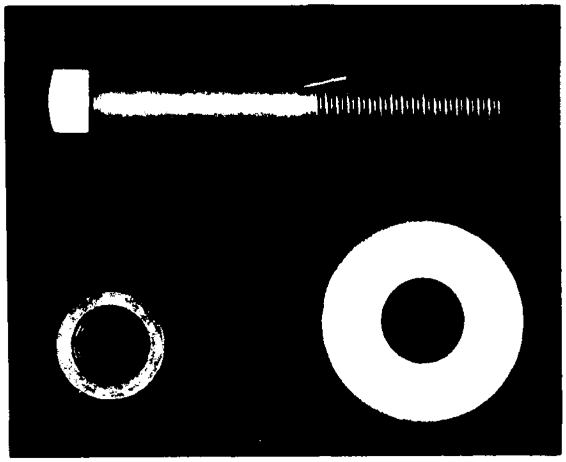
Figure 34

TACOM Fastener Controls

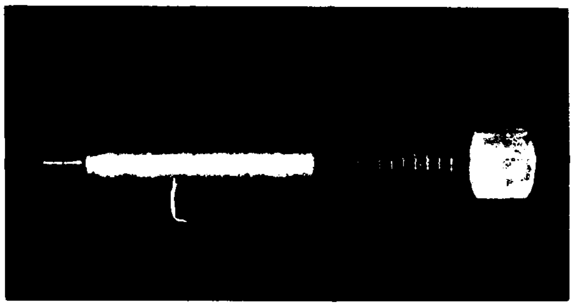
Fig. 35



Cd Control - Immersion



Initial

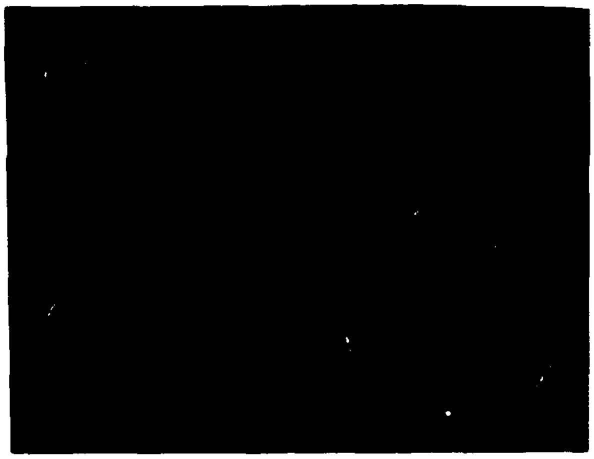


Initial

312 Hours

Figure 36

Zn Olive Drab Control - Immersion



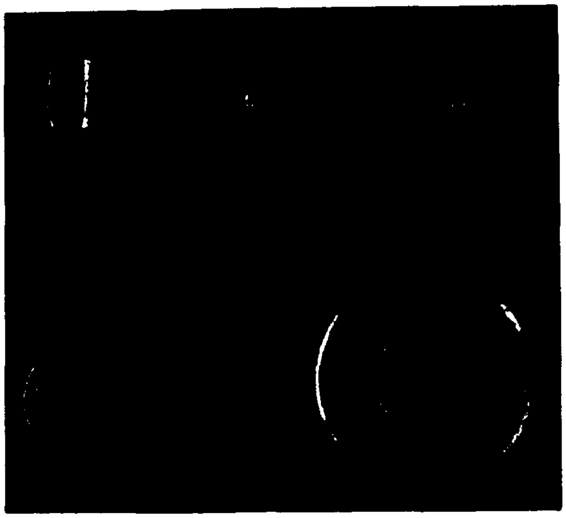
Initial

Initial

312 Hours

Figure 37

Zn-Co Control - Immersion



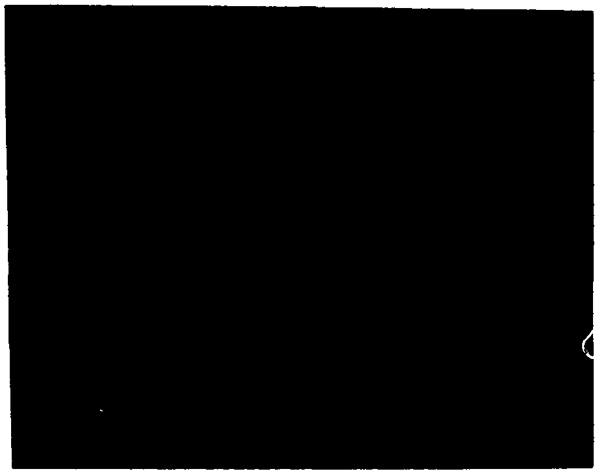
Initial

Initial

312 Hours

Figure 38

Modified Phosphate Control - Immersion



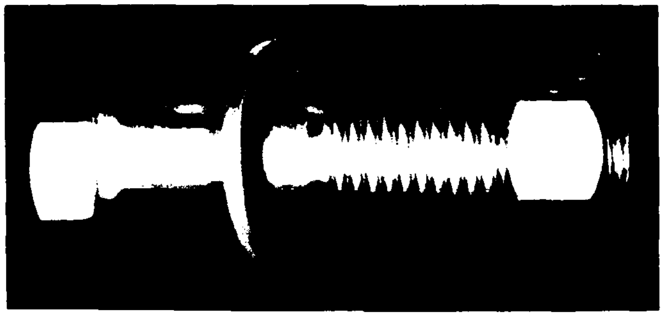
Initial

Initial

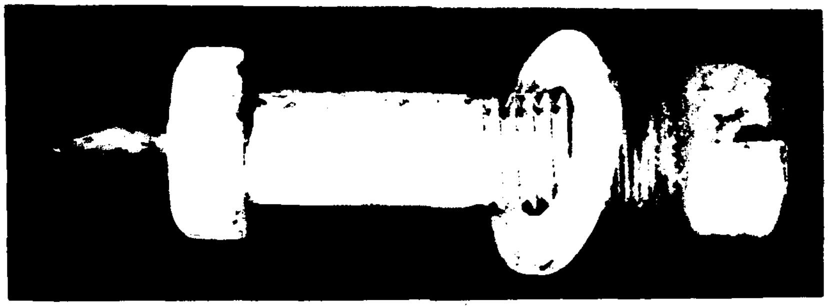
312 Hours

Figure 39

Sn-Zn Control - Immersion



Initial



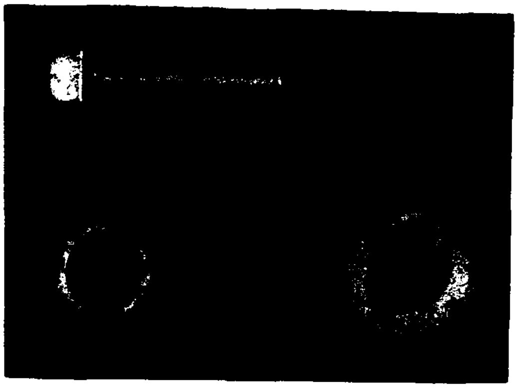
312 Hours

Bare Steel Control - Immersion

312 Hours

Figure 40

Zn-Ni Control - Immersion



Initial

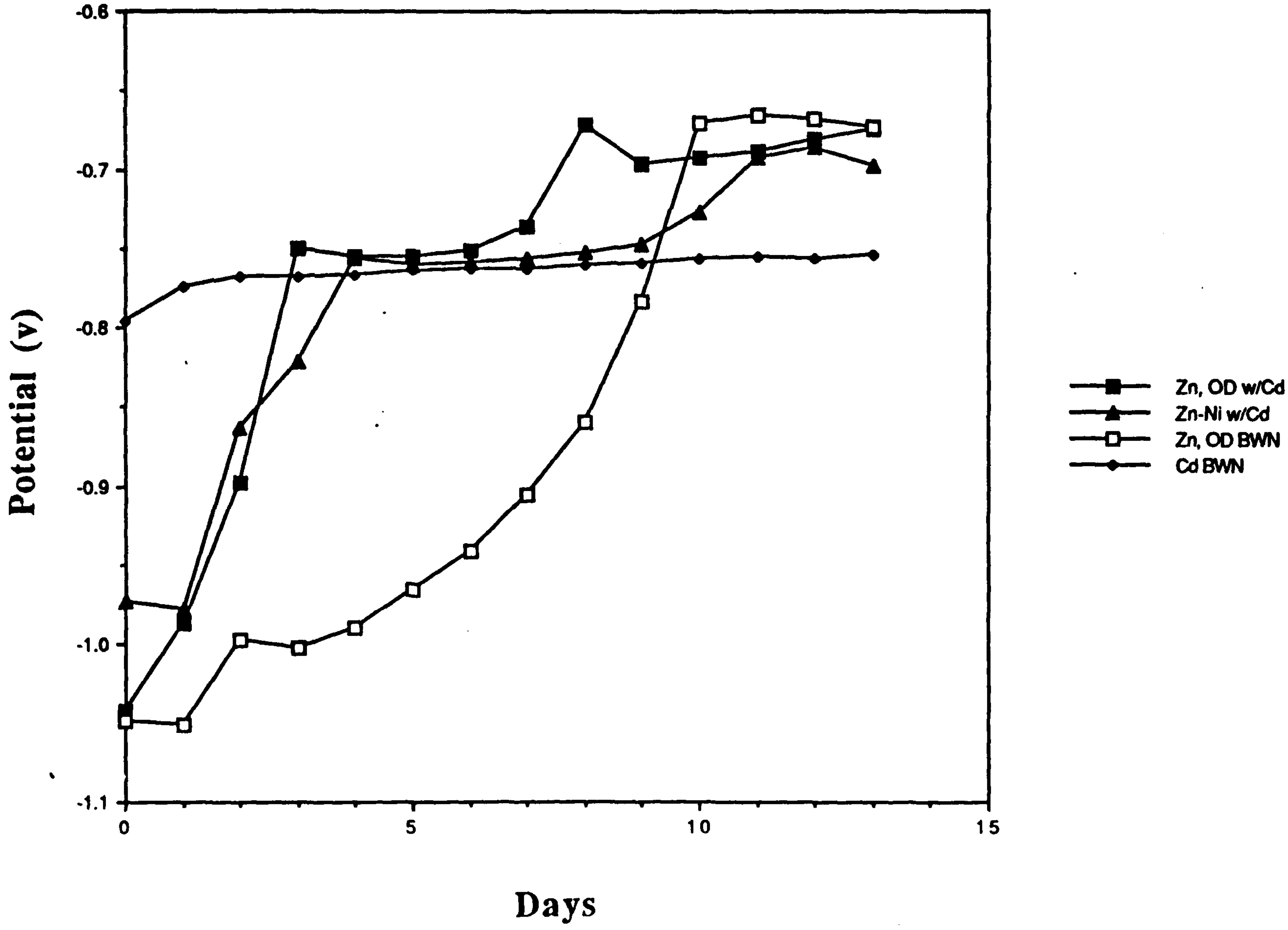
Initial

312 Hours

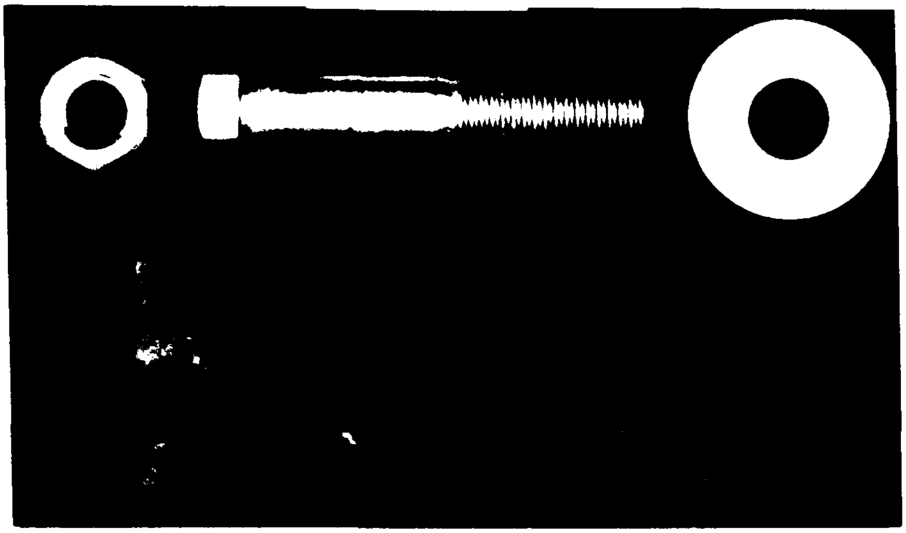
Figure 41

TACOM Fastener Joint A's

Fig. 42



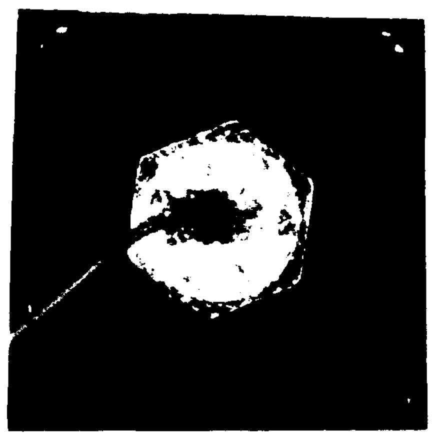
Cd (BWN) Joint A - Immersion



Initial

312 Hours

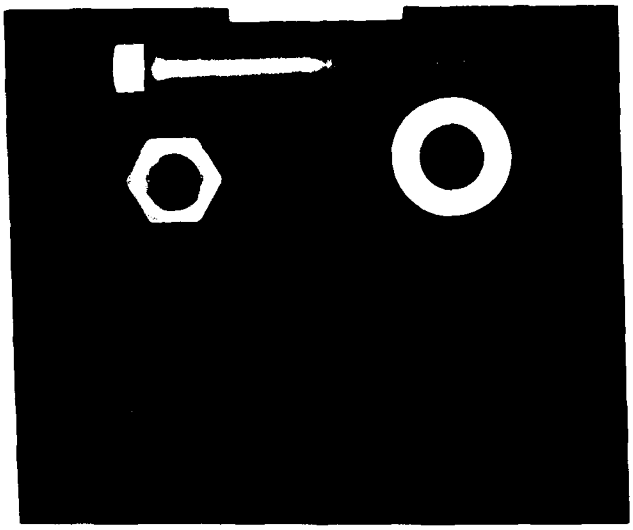
312 Hours



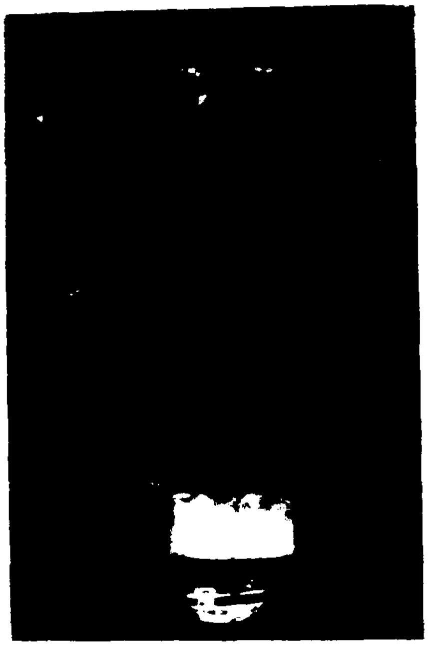
312 Hours

Figure 43

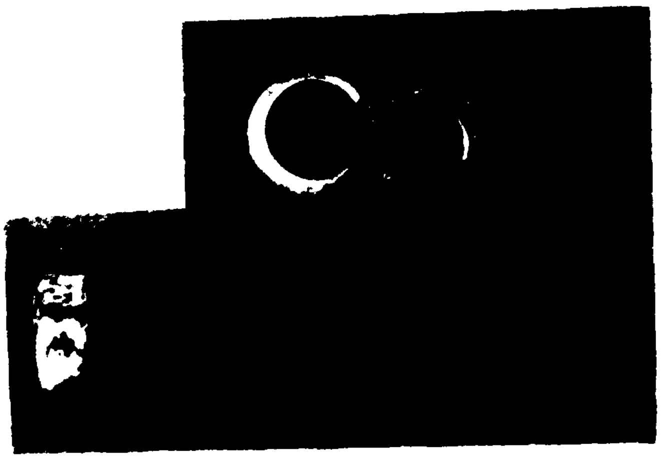
Zn-Ni with Cd, Joint A - Immersion



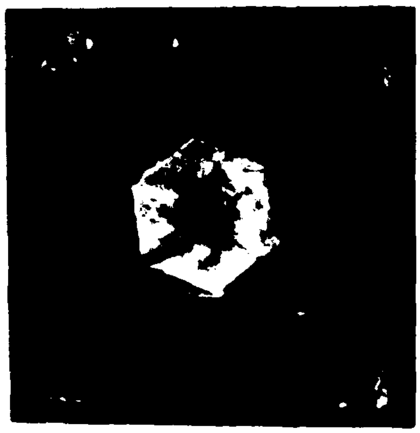
Initial



312 Hours



312 Hours



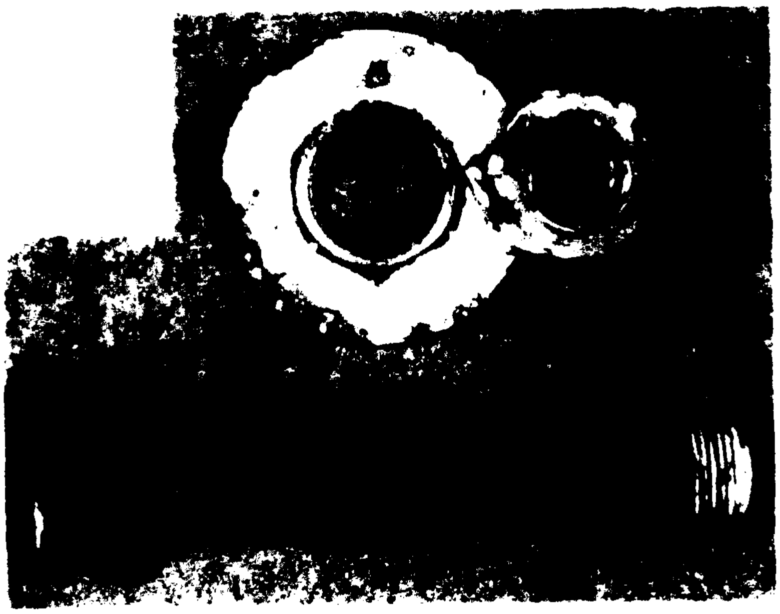
312 Hours

Figure 44

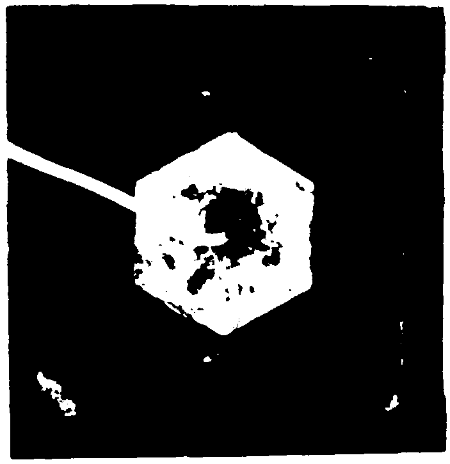
Zn Olive Drab (BWN) Joint A - Immersion

Initial

312 Hours



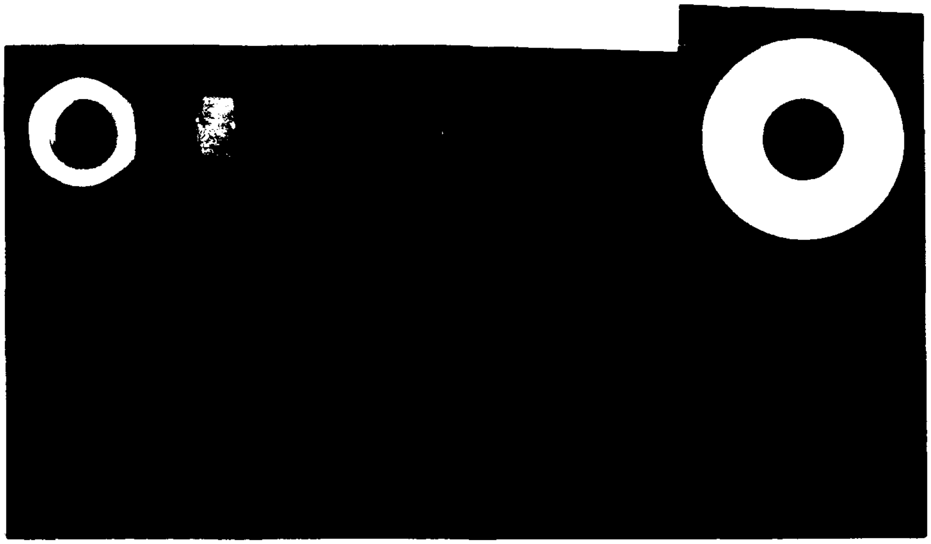
312 Hours



312 Hours

Figure 45

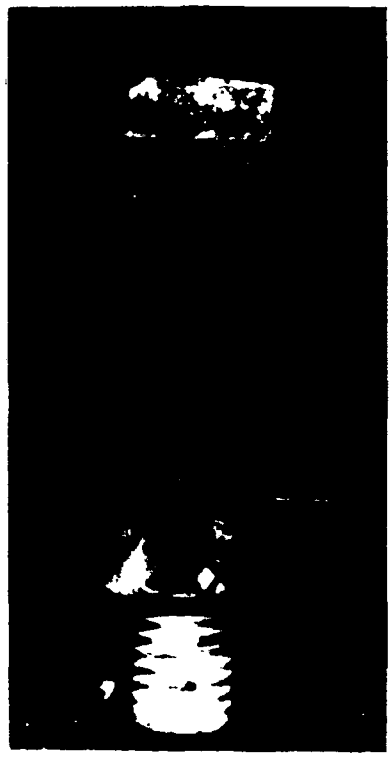
Zn Olive Drab with Cd, Joint A - Immersion



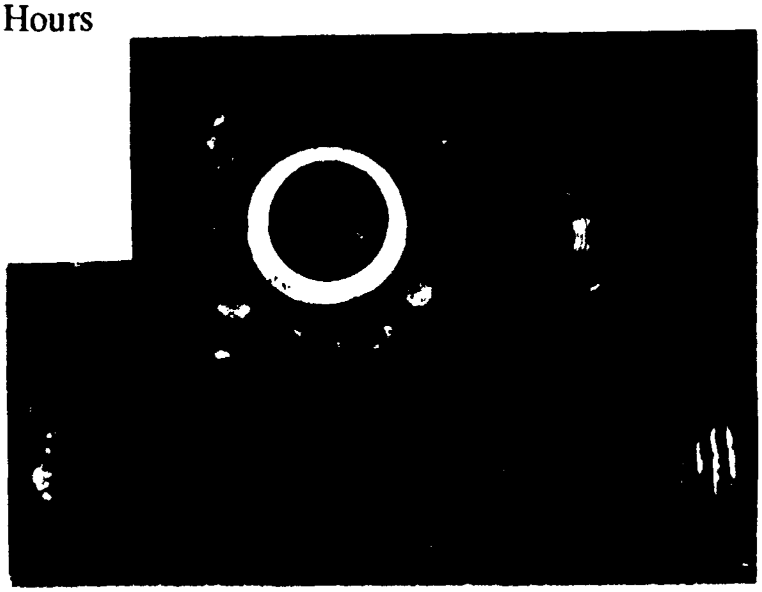
Initial

Initial

312 Hours



312 Hours

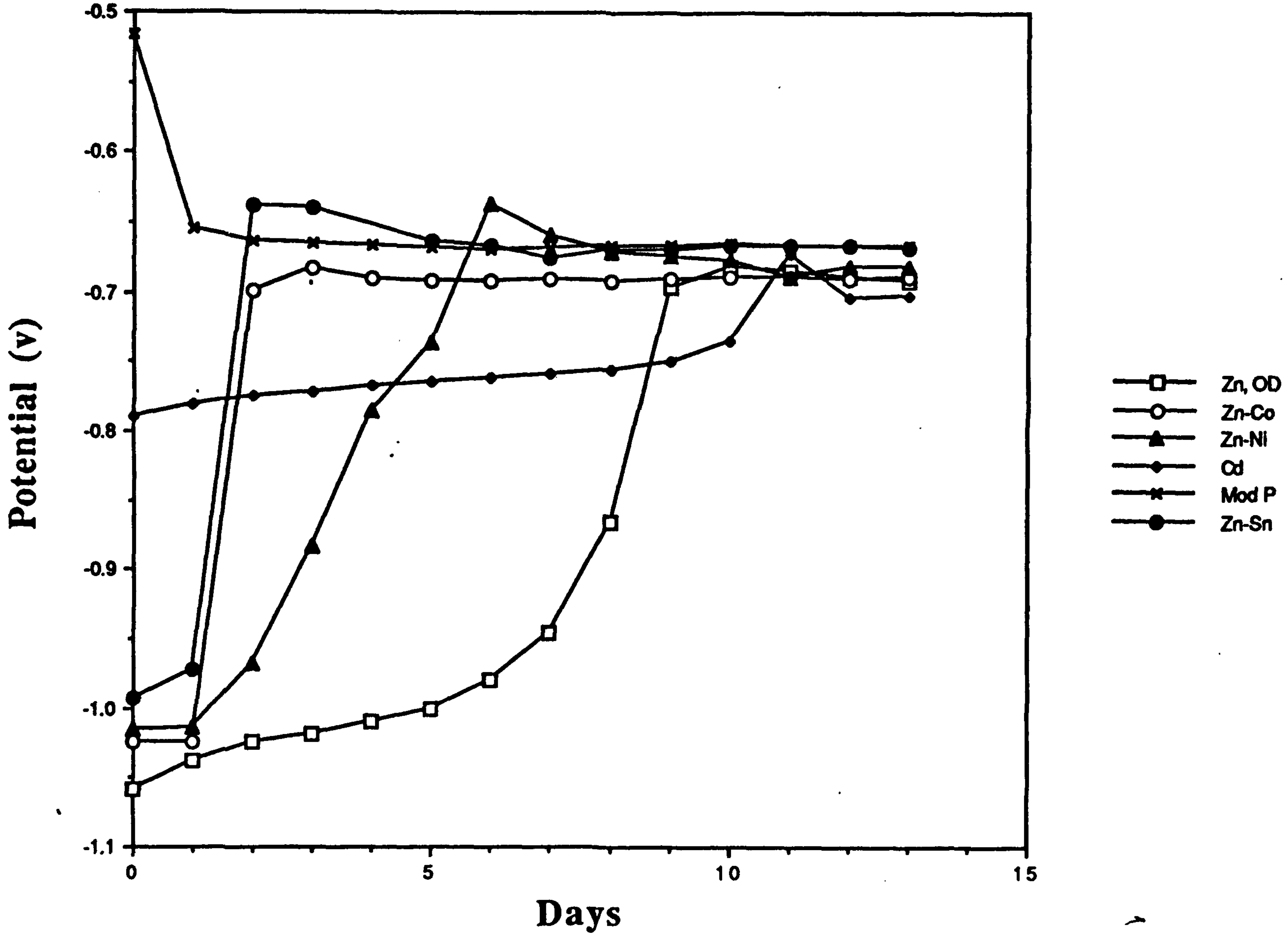


312 Hours

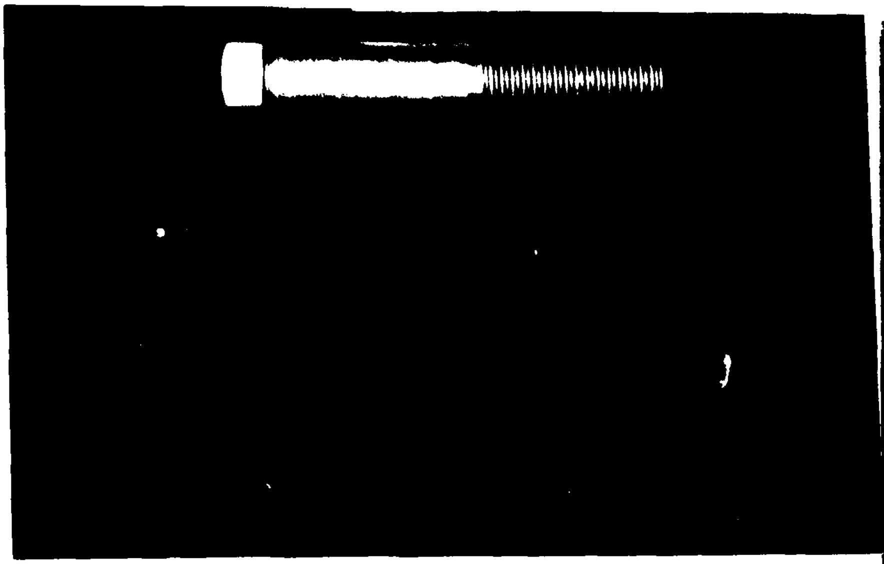
Figure 46

TACOM Fastener Joint B's

Fig. 47



Cd Joint B - Immersion



Initial

312 Hours

312 Hours

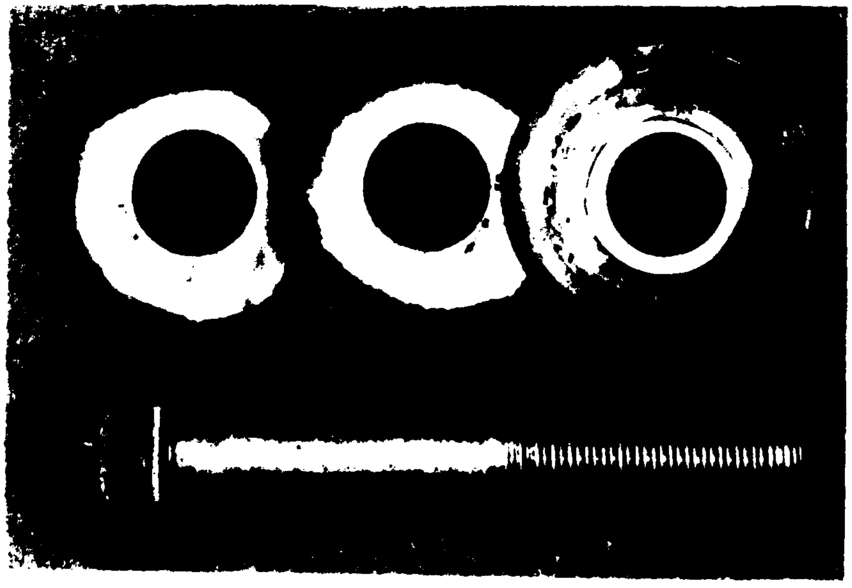
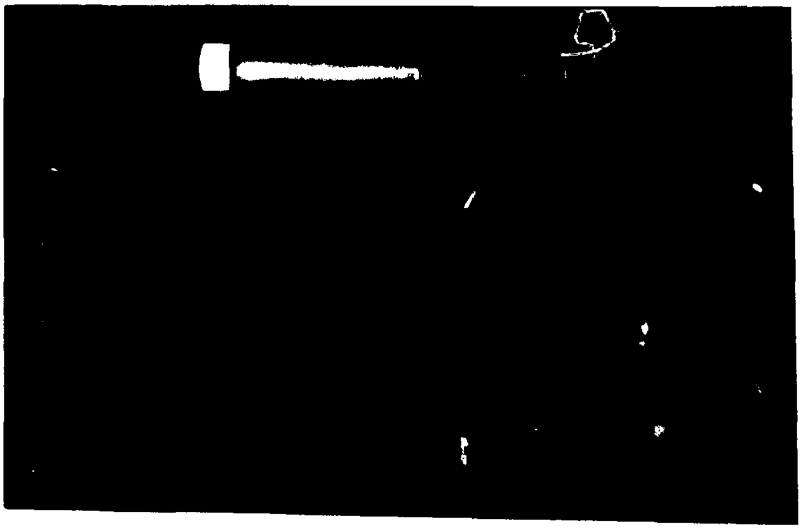


Figure 48

312 Hours

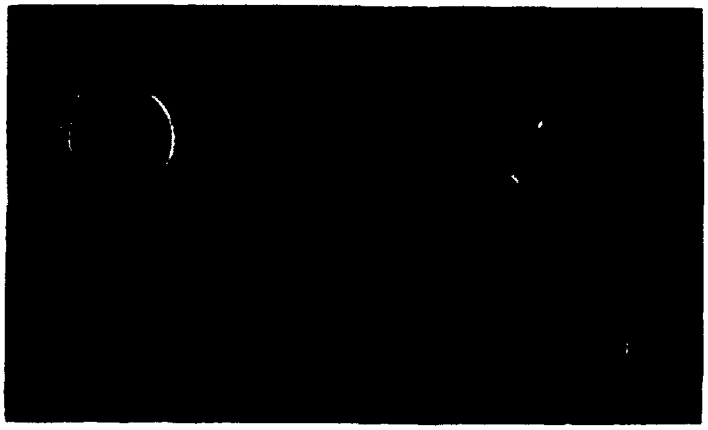
Zn-Ni Joint B - Immersion



Initial

312 Hours

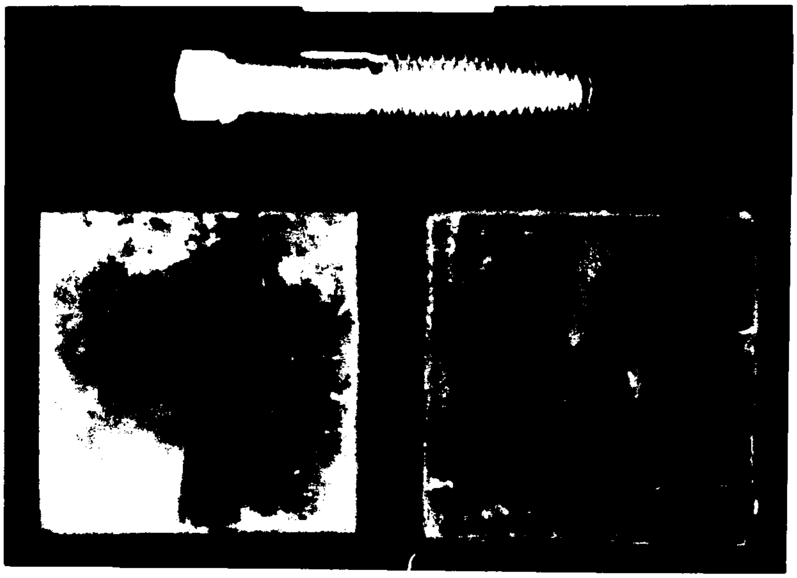
312 Hours



312 Hours

Figure 49

Sn-Zn Joint B - Immersion



Initial

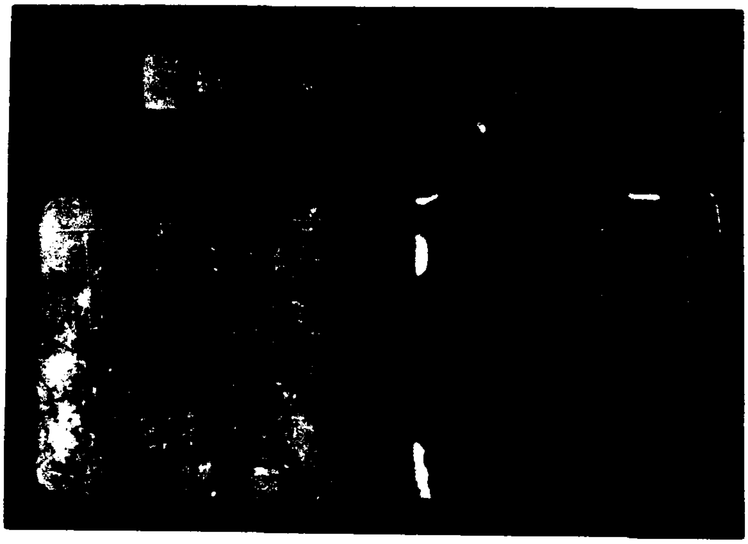
312 Hours

312 Hours

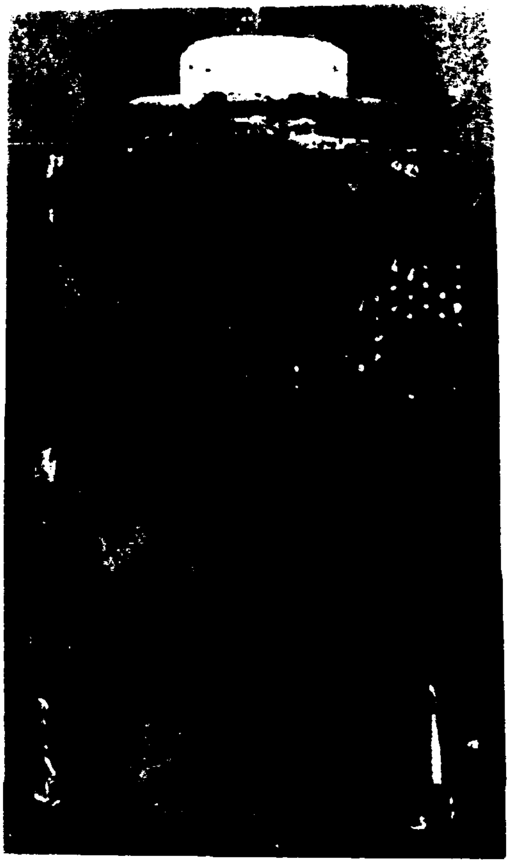
312 Hours

Figure 50

Zn Olive Drab Joint B - Immersion



Initial



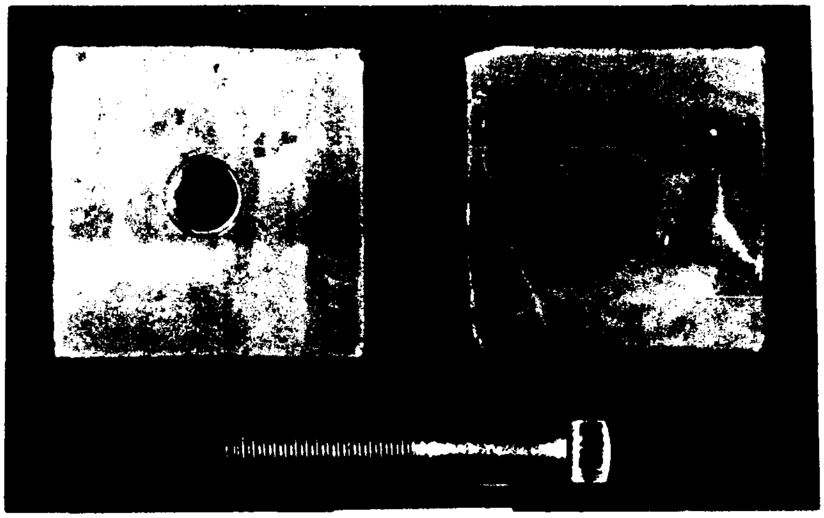
312 Hours

312 Hours

312 Hours

Figure 51

Zn-Co Joint B - Immersion



Initial

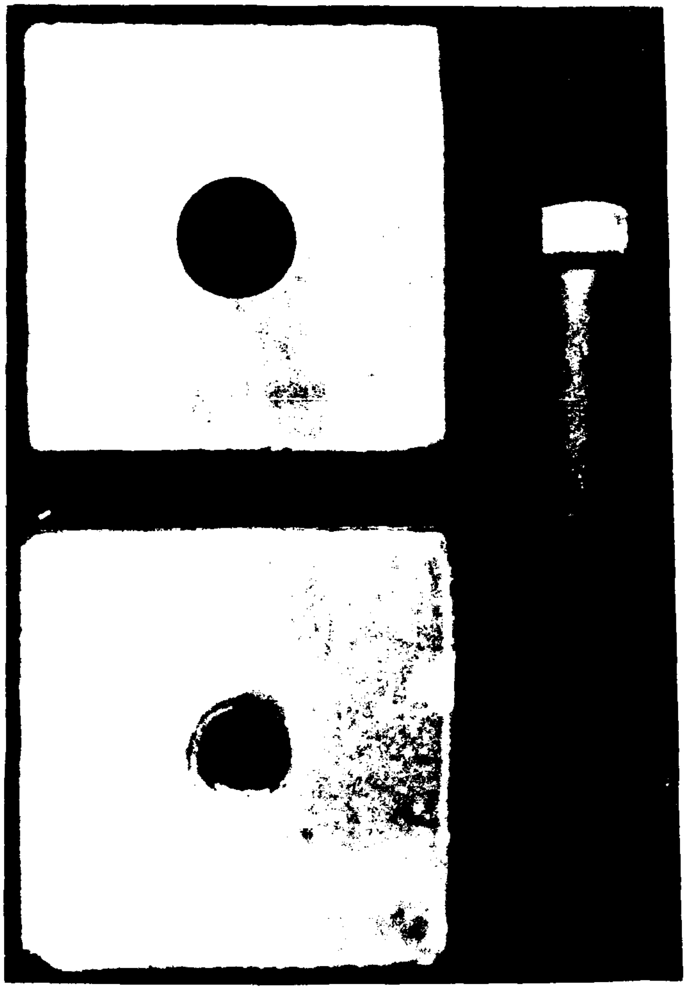
312 Hours

312 Hours

312 Hours

Figure 52

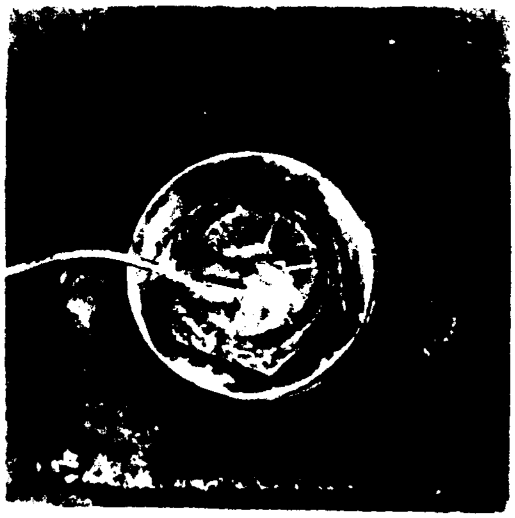
Modified Phosphate Joint B - Immersion



Initial

312 Hours

312 Hours

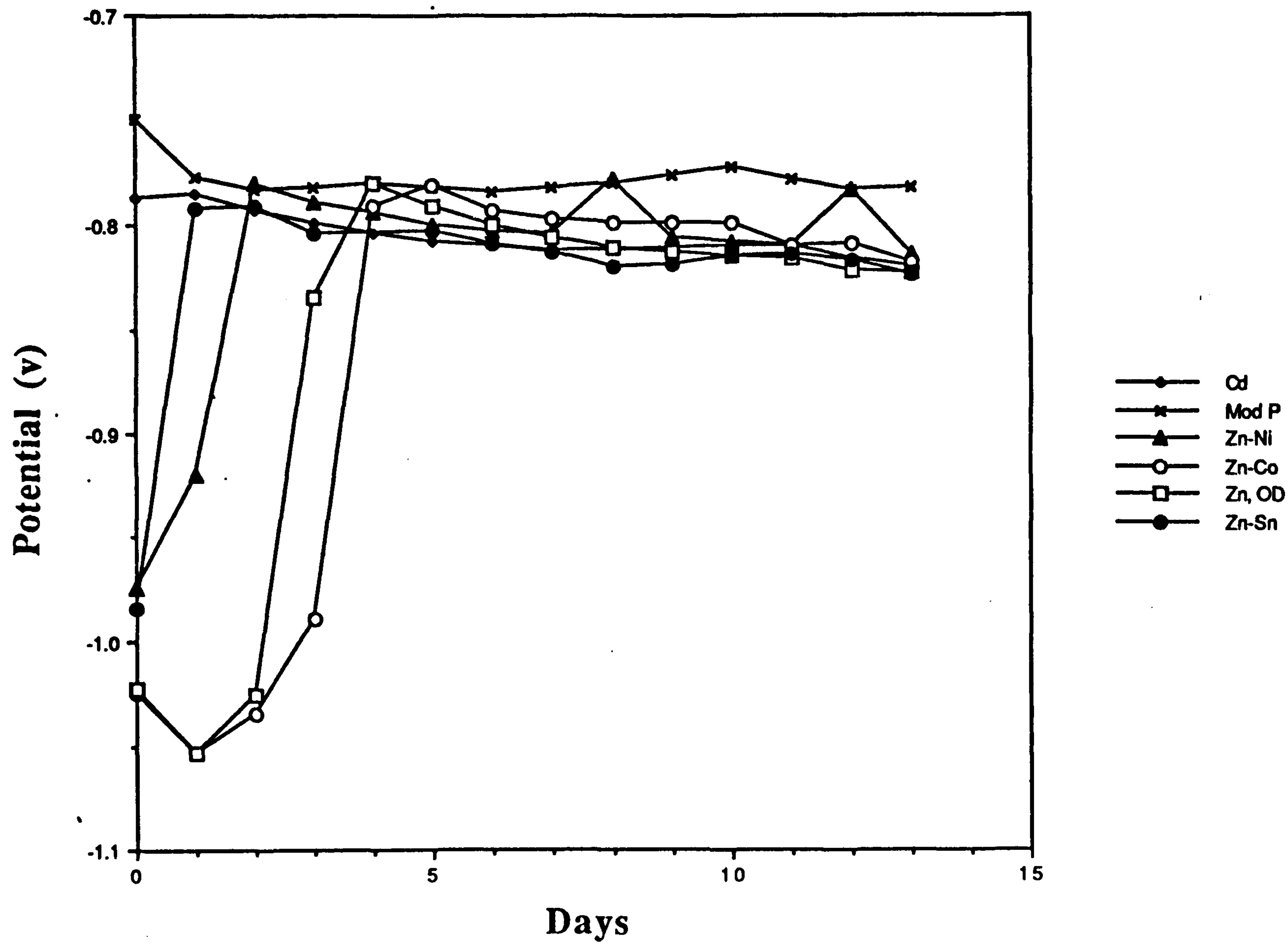


312 Hours

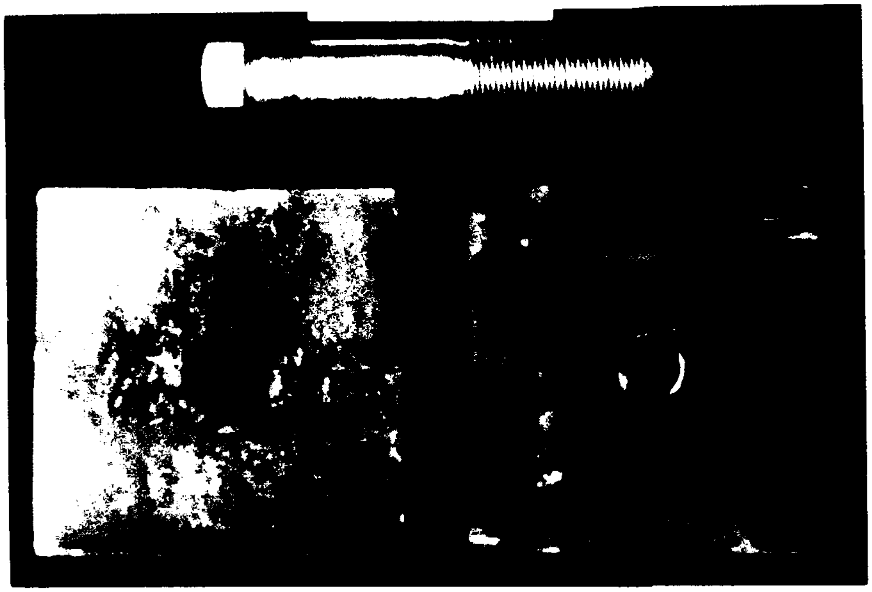
Figure 53

TACOM Fastener Joint C's

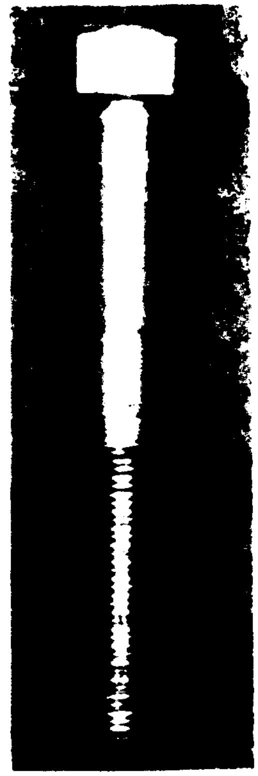
Fig. 54



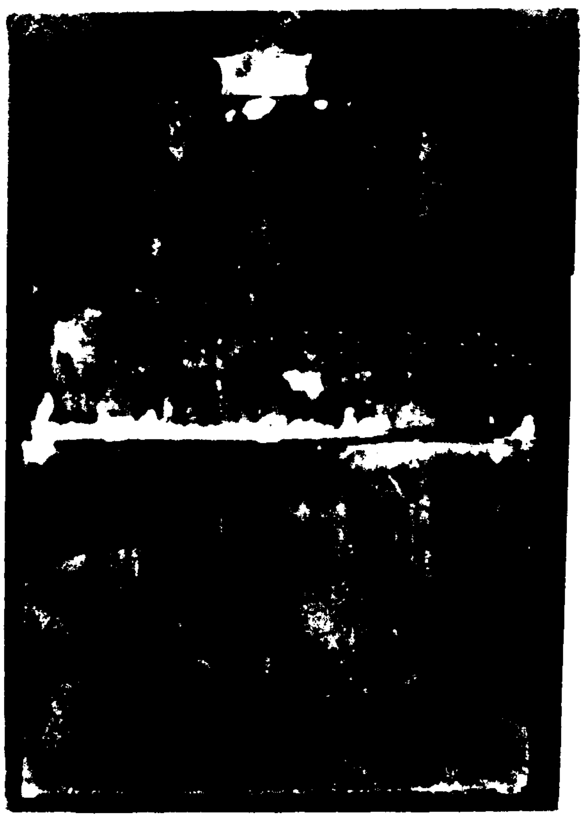
Cd Joint C - Immersion



Initial



312 Hours

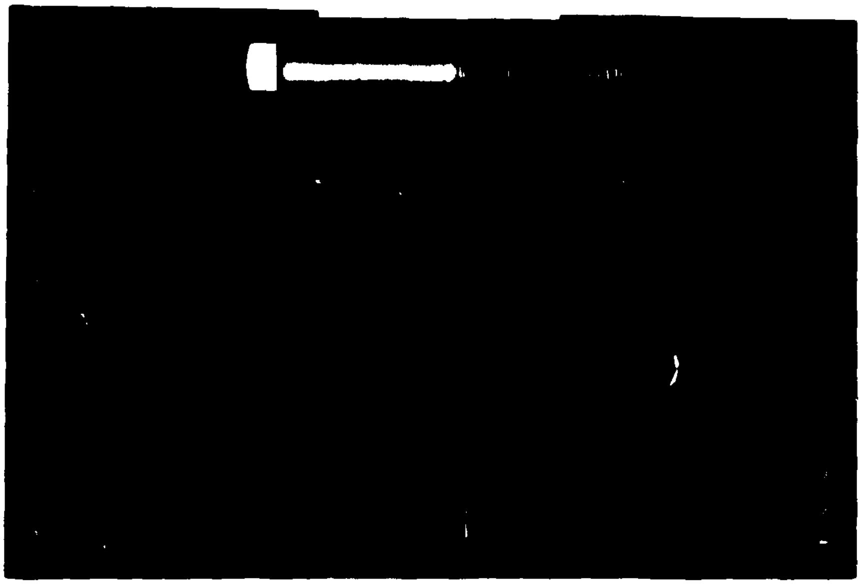


312 Hours

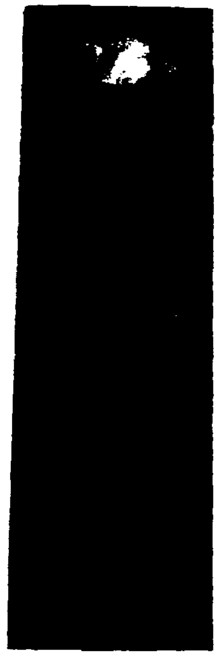
312 Hours

Figure 55

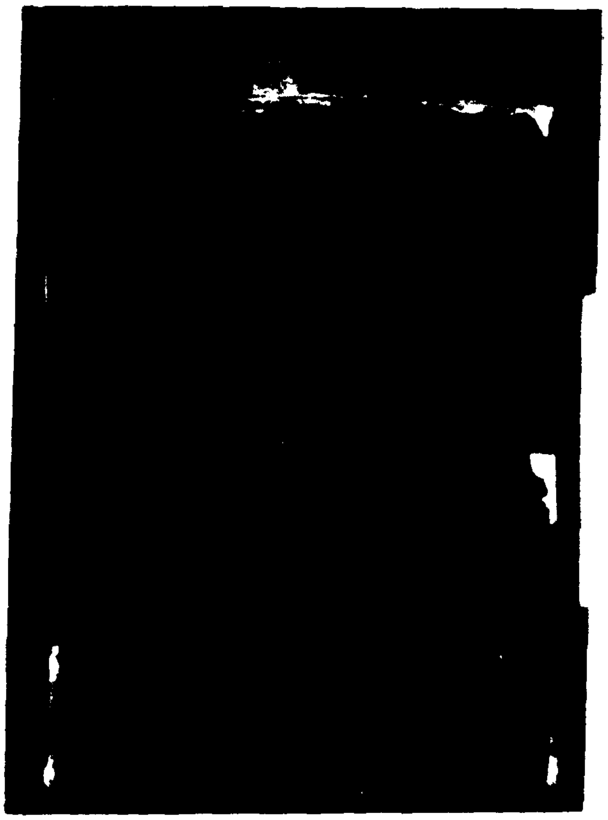
Zn-Ni Joint C - Immersion



Initial



312 Hours

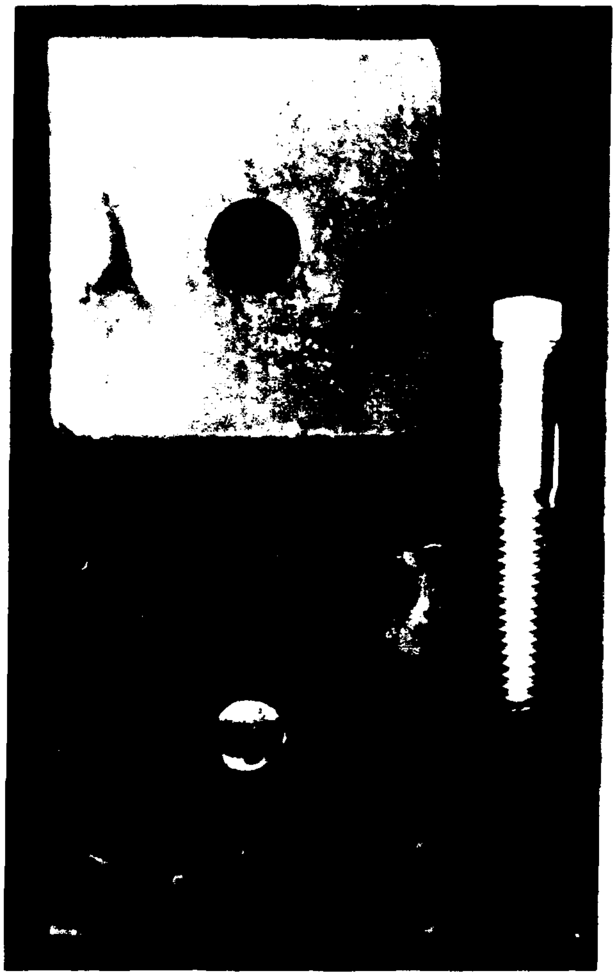


312 Hours

312 Hours

Figure 56

Sn-Zn Joint C - Immersion



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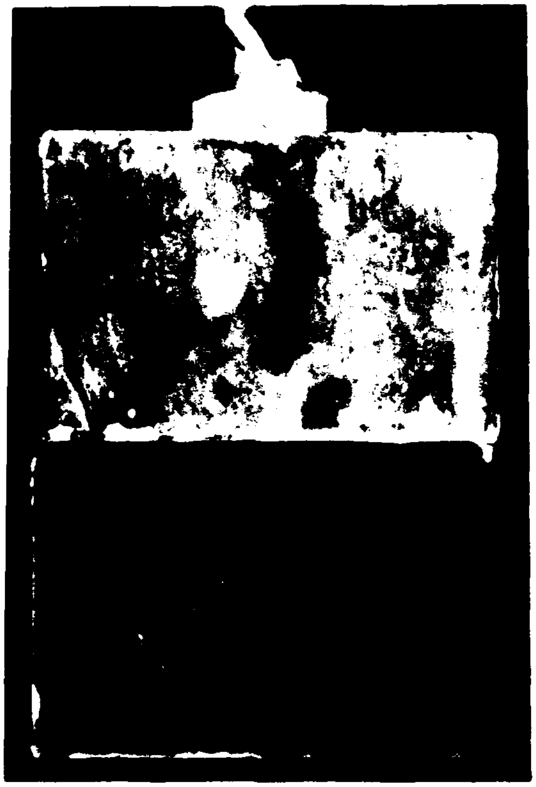
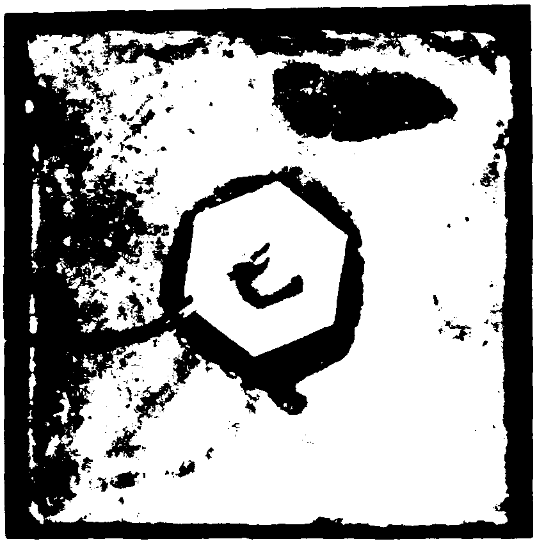


312 Hours

312 Hours

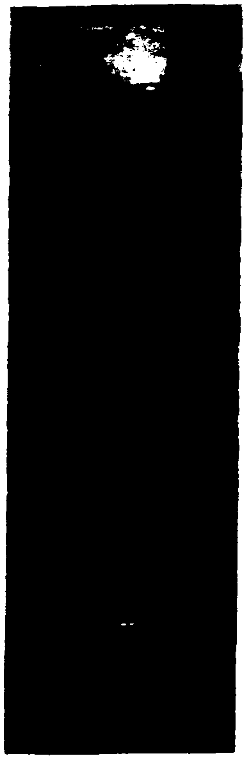


312 Hours

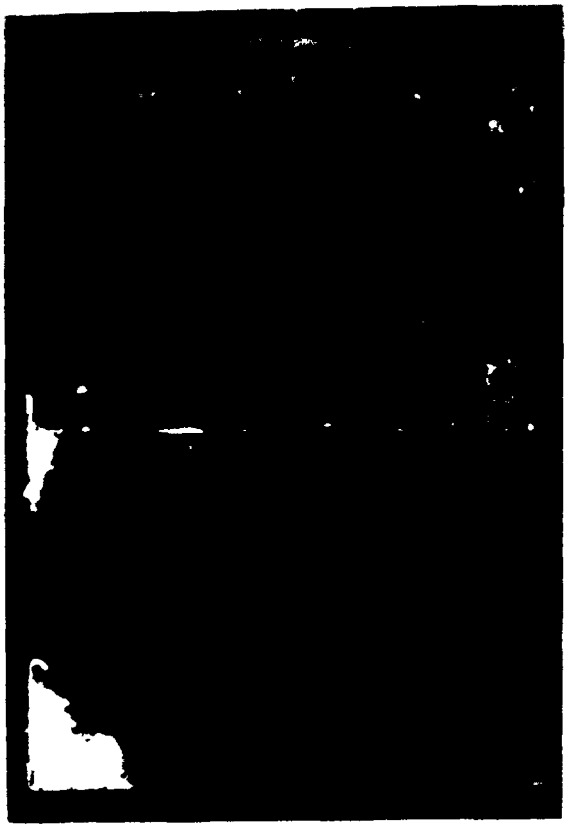
Figure 57

Zn Olive Drab Joint C - Immersion

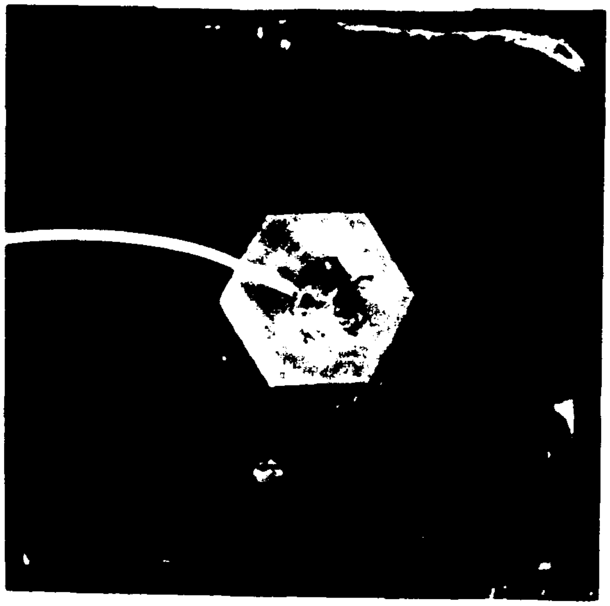
Initial



312 Hours



312 Hours

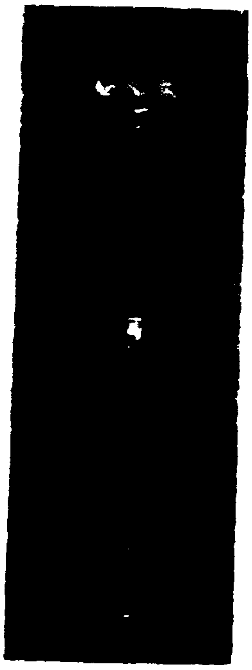


312 Hours

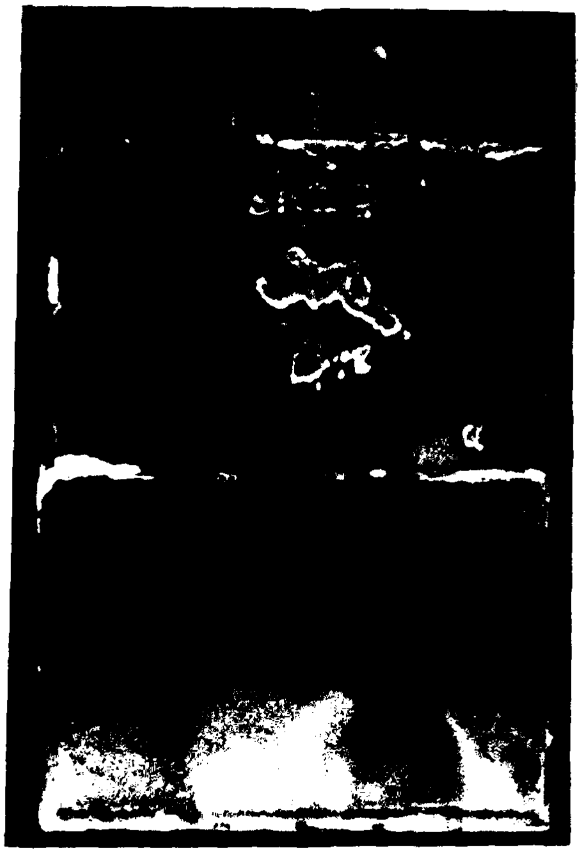
Figure 58

Zn-Co Joint C - Immersion

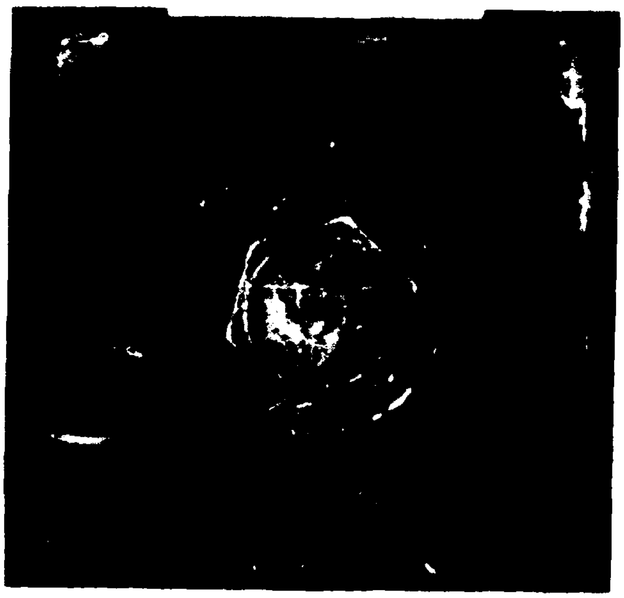
Initial



312 Hours



312 Hours



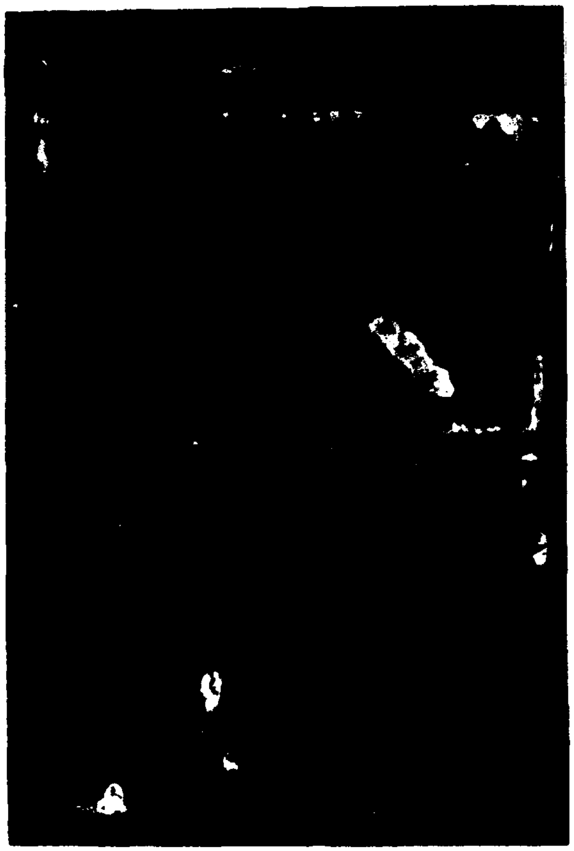
312 Hours

Figure 59

Modified Phosphate Joint C - Immersion

Initial

312 Hours



312 Hours

312 Hours

Figure 60

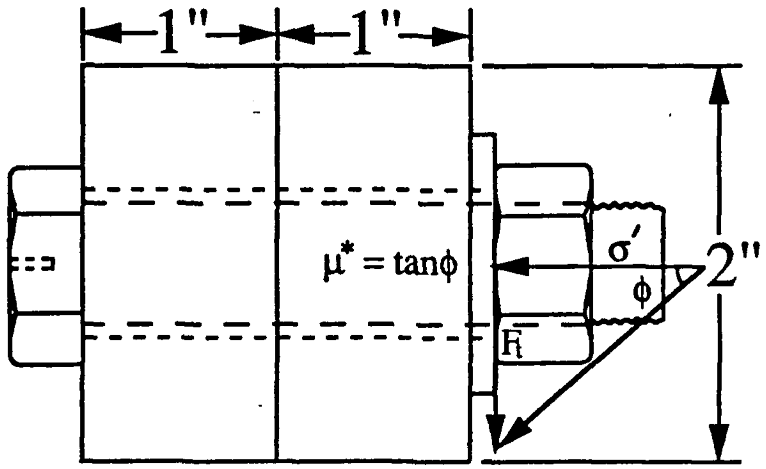


Fig. 61: Frictional stress between the nut and the washer

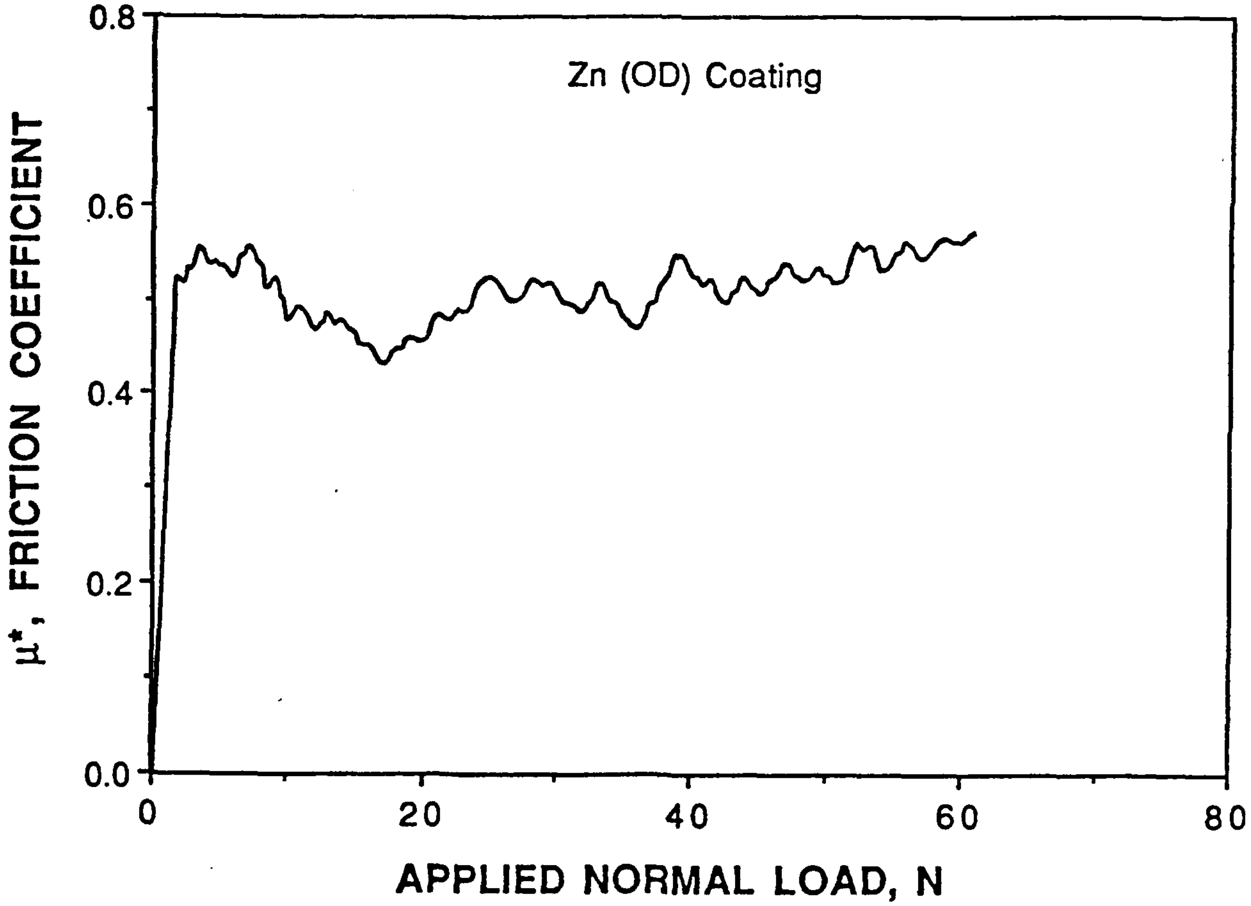
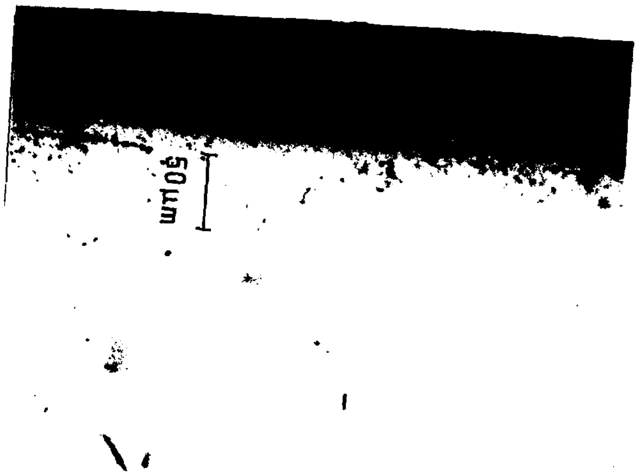
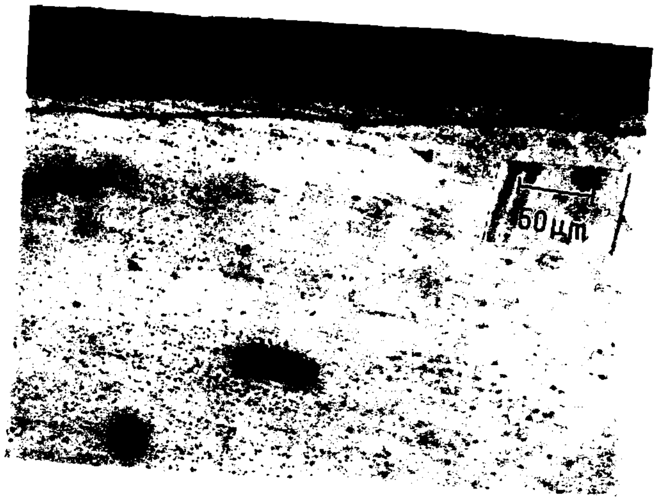


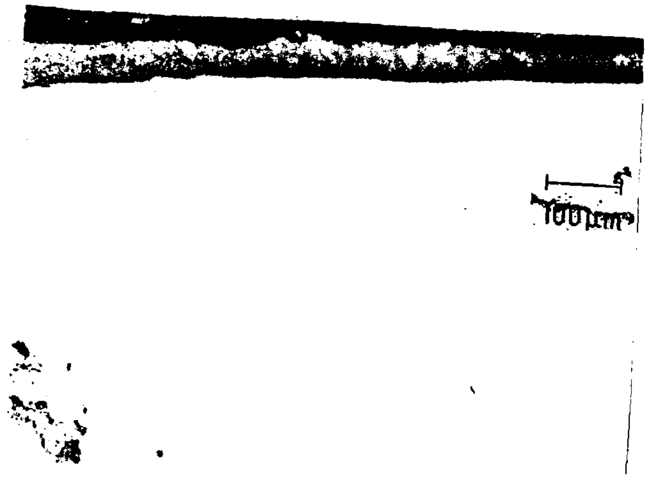
Fig. 62: Friction coefficient versus applied normal load for a Zn-coated washer.



Cadmium coating on steel washer
Coating thickness: 0.00063"

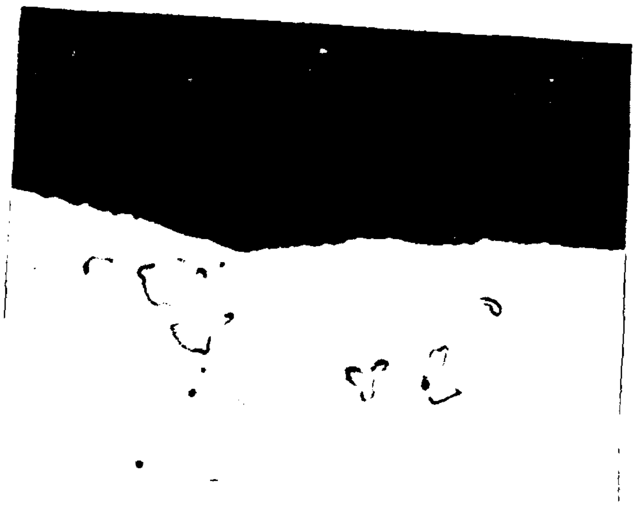


Zinc-Nickel coating on steel washer
Coating thickness: 0.00047"

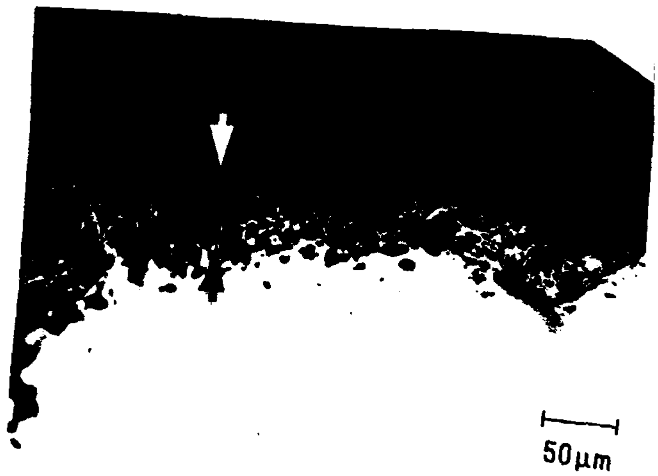


Zinc-Tin coating on steel washer
Coating thickness: 0.00204"

Zinc (OD) coating on steel washer (500X)
Coating thickness: 0.00110"



Zinc-Cobalt coating on steel washer (500X)
Coating thickness: 0.00134"



Phosphate coating on steel washer
Coating thickness: 0.00258"

Figure 63

APPENDIX A

BOLT TESTING, CORROSION STUDY - GALVANIC COUPLES

1. The test program was divided into two parts.

1.1 Test Plan A, Corrosion Study with Galvanic Couples: Current bolt coating; both Zinc and Cadmium Plating .

1.2 Test Plan B, Corrosion Study with Galvanic Couples: Proposed Future Bolt Coatings; Zinc-Nickel and Zinc-Cobalt Plating, Zn-Sn plating, and super phosphate coating.

2. Scope of work for Test Plan A

2.1 The purpose of Test Plan A is to evaluate galvanic couples in salt spray and salt water environments for bolted joints with mixed plating combinations typical in current military vehicle production and inventory.

a. Current coating requirements for standard grade 8 MS-bolts (MS-18153, MS-18154, MS-90727 and MS-90723) with zinc plating are:

(1) ASTM B633, Type II with yellow chromate finish treatment and with SC2 thickness - 8 micrometers (.0003 inch), or

(2) ASTM B633, Type II with bronze or olive drab chromate finish treatment and with SCI thickness - 5 micrometers (.0002 inch).

b. Previous coating requirement for standard grade 8 MS-bolts was cadmium plating QQ-P-416, Type II, Class 3. (Cadmium plated bolts are still in contractors' and military's supply).

c. Current coating requirement for mating fasteners (washers and nuts) that are used with grade 8, MS-bolts is cadmium plating QQ-P-4156, Type II, Class 3.

2.2 Tests shall be performed as described below using MS-fastener, galvanic couples, torque clamping loads and typical joint designs used in currently produced combat (M1A1, M2 and M3) and tactical (M939) vehicles.

2.2.1 Test Group 1 shall be tested in a salt spray environment as specified in ASTM-B117.

2.2.1.1 Test Group 1 shall consist of bolted specimens, Joints A, B, C etc. and control samples, CS-1, CS-2, CS-3 etc., as shown in Table 1: Galvanic Couples in Salt Spray Test.

2..2.1.2 Control samnles shall be single fasteners (bolt, nut and washer) with plated coatings similar to those used in the specified joints and salt spray tested with the bolted joint specimens. (Note: For a valid test for Group 1, control samples should meet minimum salt spray requirement of 96 hours for zinc or cadmium plating, Type II).

2.2.1.3 Bolted joint specimens, shall be assembled with fasteners and materials as specified in Table 1; torqued to the specified values with a calibrated torque wrench; and salt spray tested.

2.2.1.4 During the salt spray test of Test Group 1, the following characteristics shall be monitored and recorded:

a. Determine hours to appearance of white corrosion products for each bolted joint specimen and each control sample.

b. Record location of white corrosion products for each specimen in item "a" . above.

c. Determine hours to appearance of red corrosion or base metal corrosion products and its location on each specimen and each control sample.

2.2.1.5 Testing for Group 1 shall be terminated when all test information has been obtained or at the discretion of MTL.

2.2.2 Test Group 2 shall be tested in a salt water environment.

2.2.2.1 Group 2 shall consist of bolted specimens, Joints A, B, C, etc. and control samples CS-1, CS-2, CS-3 etc., as shown in Table 2: Galvanic Couples in Salt Water Test.

2.2.2.2 Control samples shall be single fasteners (bolt, nut and washer) with plated coating similar to those used in the specified joints and salt water tested with the bolted joint specimens.

2.2.2.3 Bolted Joint specimens, shall be assembled with fasteners and materials as specified in Table 2; torque to the specified value(s) with a calibrated torque wrench; assembled with electrochemical monitoring system and salt water tested.

2.2.2.4 During the salt water test of Group 2, the following characteristics shall be monitored and recorded.

a. Potential, EMF, for each bolted joint specimen as a function of exposure time.

b. Determine anode and cathode for each couple monitored.

c. Determine hours to evidence of corrosion for each bolted joint specimen and control sample.

d. Determine type of corrosion and its location for each specimen in item "a" . above.

2.2.2.5 Testing for Group 2 shall be terminated when all test information has been obtained or at the discretion of MTL.

3. Scope of Work for Test Plan B.

3.1 The purpose of Test Plan B is to evaluate galvanic couples that may occur in future bolted joints for military vehicles in salt spray and salt water environments when alternate bolt coatings are used in lieu of zinc or cadmium plating.

3.2 Fasteners (bolts, nuts and washers) tested in Plan B will have the following new/different coatings which are currently being investigated for military applications. (These coating do not have military specifications).

a. Zinc-cobalt electroplated coating (0.5 to 1.0 percent Co)

b. Zinc-nickel electroplated coating

c. Modified phosphate coating

d. Sn-Zn electrodeposited coating.

3.3 Tests shall be performed as described below using; available fasteners with new coatings (above), galvanic couples with current fasteners (zinc and/or cadmium), torque clamping loads and some typical joint designs used in current military vehicles. Also test for coefficient of friction for each type of coating.

3.3.1 Test Group 3 shall be tested in a salt spray environment as specified in ASTM-B117.

3.3.1.1 Group 3 shall consist of bolted specimens and control samples as shown in Table 3. Galvanic Couples for Future Fastener Coatings in Salt Spray Test.

3.3.1.2 Preparation of test specimens and the test procedure shall be the same as paragraphs 2.2.1.2 through 2.2.1.5 above, except fasteners and materials shall be specified in Table 3.

3.3.2 Test Group 4 shall be tested in a salt water environment.

3.3.2.1 Group 4 shall consist of bolted specimens and control samples as shown in Table 4: Galvanic Couples for Future Fasteners Coating in Salt Water Test.

3.3.2.2 Preparation of test specimens and the test procedure shall be the same as paragraphs 2.2.2.1 through 2.2.2.5 above, except fasteners and materials shall be as specified in Table 4.

JOINT A: (see figure 2)	SPECIMEN A-1	SPECIMEN A-2	CONTROL SAMPLES
Bolt Through Steel with Cd plated nut and washer			
Bolt: MS 90728 (5/8-11x3 UNC-2A)	1-Zn	1-Cd	1-Zn
Washer:	1-Cd	1-Cd	1-Cd
Nut:	1-Cd	1-Cd	1-Cd
Steel: (SAE 4130 or 4140; Rc 30-35)	2-2"x2"x1"	2-2"x2"x1"	
Torque, Ft-Lbs: wet (lub)	180*	180*	

JOINT B: (see figure 3)	SPECIMEN B-1	SPECIMEN B-2	CONTROL SAMPLES
Bolt Through Steel threaded into armor steel			
Bolt: MS	1-Zn	1-Cd	1-Zn
Steel: (SAE 4130 or 4140; Rc 30-35)	2-2.5"x2.5"x1"	2-2.5"x2.5"x1"	
Armor Steel: MIL-A-12560 Class-1	1-2.5"x2.5"x2.5"	1-2.5"x2.5"x2.5"	
Torque, Ft-Lbs: wet (lub)	180*	180*	

JOINT C: (see figure)	SPECIMEN C-1	SPECIMEN C-2	CONTROL SAMPLES
Bolt Through armor steel threaded into aluminum armor with stainless steel insert			
Bolt: MS	1-Zn	1-Cd	1-Zn 1-CdWasher:
Nut:	1	1	
Insert: threaded stainless steel			
Armor Steel: MIL-A-12560, Cl-1 or MIL-A- 46100	1-3"x3"x2"	1-3"x3"x2"	
Aluminum Armor: 5083	1-3"x3"x2"	1-3"x3"x2"	
Torque, Ft-Lbs: wet (lub)	180*	180*	

* Torque values for coated assemblies were 180 ft/lbs except for the Zn-Ni coated assemblies which were 90 ft/lbs (bolt diameter was 0.50" instead of 0.625")

TEST PLAN A

Corrosion Study: Current Bolt Coating,
Zinc/Cadmium Plating- Galvanic Couples

Table 1 -Galvanic Couples in Salt Spray Test (ASTM-B117)

Bolt:	MS-90728-168	MS-90728-168	MS-90728-168
Bolt Plating:	Zinc	Cadmium	1-Zinc(Control) 1-Cadmium (Control)
Conversion Coating Type:	II	II	II
Actual Conversion Coating:	Bronze or O.D. Chromate	Yellow Chromate	Zn + Bronze or O.D. Chromate
Washer:	5/8"-11	5/8"-11	1-Cd (Control)
Nut:	5/8"	5/8"	1-Cd (Control)
Joint A Bolt through steel with Cadmium plated nut and washer	1	1	
Joint B Bolt through steel into threaded armor steel	1	1	
Joint C Bolt through armor steel threaded into aluminum armor with stainless steel inserts	1	1	
MONITOR:			
1. Hours to White Corrosion Products	x	x	x
2. Hours to Red Corrosion Products	x	x	x

TEST PLAN A

Corrosion Study: Current Bolt Coating,
Zinc/Cadmium Plating- Galvanic Couples

Table 2 -Galvanic Couples in Salt Water Test

Bolt:	MS-90728-168	MS-90728-168	MS-90728-168
Bolt Plating:	Zinc	Cadmium	1-Zinc(Control) 1-Cadmium (Control)
Conversion Coating Type:	II	II	II
Actual Conversion Coating:	Bronze or O.D. Chromate	Yellow Chromate	Zn + Bronze or O.D. Chromate
Washer:	5/8"-11	5/8"-11	1-Cd (Control)
Nut:	5/8"	5/8"	1-Cd (Control)
Coatings:		Cd Type II	
Joint A Bolt through steel with Cadmium plated nut and washer	1	1	
Joint B Bolt through steel into threaded armor steel	1	1	
Joint C Bolt through armor steel threaded into aluminum armor with stainless steel inserts	1	1	
MONITOR:			
1. Potential, EMF	x	x	x
2. Determine Anode & Cathode of couple	x	x	
3. Hours to Corrosion	x	x	x
4. Determine type of Corrosion	x	x	x

TEST PLAN B

Corrosion Study: Potential Future Bolt Coatings,
Galvanic Couples

Table 3 -Galvanic Couples in Salt Spray Test (ASTM-B117)

Bolt:	MS-90728-168 (5/8-11x3 UNC-2A)	MS-90728-168	MS-90728-168	MS-90728-119 (1/2"-13x3 UNC-2A)	MS-90728-168
Bolt Plating:	Zinc-Cobalt	Zinc-Nickel	New Phosphate Coating	Zinc-Tin	1 Zn-Co (Control) 1 Zn-Ni (Control) 1 New Phos (Control)
Washer:	5/8"-11	5/8"-11	5/8"-11	1/2"-13 x 3"	1-each (Control)
Nut:	5/8"	5/8"	5/8"	1/2"	1-each (Control)
Coating:	Zinc-Cobalt (and Cd Type II)	Zinc-Nickel	New Phosphate	Zinc-Tin	1-each (Control)
Joint Type			**Specimen Quantity**		
Joint A Bolt through steel with compatible coated nut	2	2	2	2	
Joint B Bolt through steel into threaded armor steel	1	1	1	1	
Joint C Bolt through armor steel threaded into aluminum armor with stainless steel inserts	1	1	1	1	
MONITOR:					
1. Hours to White Corrosion Products	x	x	x	x	x
2. Hours to Red Corrosion Products	x	x	x	x	x

TEST PLAN B

Corrosion Study: Potential Future Bolt Coatings,
Galvanic Couples

Table 4 -Galvanic Couples in Salt Water Test

Bolt:	MS-90728-168 (5/8-11x3 UNC-2A)	MS-90728-168	MS-90728-168	MS-90728-119 (1/2"-13x3 UNC-2A)	MS-90728-168
Bolt Plating:	Zinc-Cobalt	Zinc-Nickel	New Phosphate Coating	Zinc-Tin	1 Zn-Co (Control) 1 Zn-Ni (Control) 1 New Phos (Control)
Washer:	5/8"-11	5/8"-11	5/8"-11	1/2"-13 x 3"	1-each (Control)
Nut:	5/8"	5/8"	5/8"	1/2"	1-each (Control)
Coating:	Zinc-Cobalt (and Cd Type II)	Zinc-Nickel	New Phosphate	Zinc-Tin	1-each (Control)
Joint Type		**Specimen Quantity**			
Joint A Bolt through steel with compatible coated nut	2	2	2		
Joint B Bolt through steel into threaded armor steel	1	1	1	1	
Joint C Bolt through armor steel threaded into aluminum armor with stainless steel inserts	1	1	1	1	
MONITOR:					
1. Potential, EMF	x	x	x	x	x
2. Determine Anode and Cathode of Couple	x	x	x	x	
3. Hours to Corrosion	x	x	x	x	x
4. Determine type of Corrosion	x	x	x	x	x

APPENDIX B

1. SCOPE

This drawing covers the requirements for electrodeposited zinc-nickel alloy plating.

1.1 Classification. Zinc-nickel alloy plating shall be of the following classes and types:

1.1.1	Class 1	-	0.00070 inches thick minimum
	Class 2	-	0.00050 inches thick minimum
	Class 3	-	0.00030 inches thick minimum
	Class 4	-	0.00020 inches thick minimum

1.1.2	Type I	-	As plated
	Type II	-	With supplementary chromate treatment
	Type III	-	With supplementary phosphate treatment

2. APPLICABLE DOCUMENTS

2.1 The following documents, of the issue in effect on the date of invitation for bids, form a part of this drawing to the extent specified herein:

SPECIFICATIONS

FEDERAL

TT-C-490 - Cleaning Methods and Pretreatment of Ferrous Surfaces for Organic Coatings

MILITARY

MIL-S-5002 - Surface Treatments and Inorganic Coatings for Metal Surfaces of Weapons Systems

STANDARDS

FEDERAL

FED-STD-151 - Metals, Tests Methods

MILITARY

MIL-STD-105 - Sampling Procedures and Tables for Inspection by Attributes

MIL-STD-1312 - Fasteners, Test Methods

(Copies of specifications, standards, drawings, and publications required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

2.2 Other Publications. The following documents form a part of this drawing to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted shall be those listed in the issue of the DODISS specified in the solicitation. Unless otherwise specified, the issues of documents not listed in the DODISS shall be the issue of the non-Government documents which is current on the date of the solicitation.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

ASTM B 117	-	Salt Spray (Fog) Testing
ASTM B 244	-	Thickness of Anodic Coatings on Aluminum and of Other Nonconductive Coatings on Nonmagnetic Basis Metals with Eddy-Current Instruments, Measurements, of
ASTM B 489	-	Metal and Oxide Coating Thickness by Microscopical Examination of a Cross Section, Measurement of
ASTM- B 499	-	Coating Thicknesses by Magnetic Method: Nonmagnetic Coatings of Magnetic Basis Metals, Measurement of
ASTM B 504	-	Thickness of Metallic Coatings by the Coulometric Method, Measurement of
ASTM B 567	-	Coating Thickness by the Beta Backscatter Method, Measurement of
ASTM B 568	-	Coating Thickness by X-Ray Spectrometry, Measurements of

(Application for copies should be addressed to the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.)

3. REQUIREMENTS

3.1 Materials. The materials used shall be such as to produce platings which meet the requirements of this drawing.

3.2 General Requirements.

3.2.1 High Tensile Strength Steel Parts. Unless otherwise specified, steel parts having an ultimate tensile strength greater than 240,000 pounds per square inch (psi) shall not be plated without specific approval of the procuring activity (see 6.2).

*3.2.2 Stress Relief Treatment. Unless otherwise specified, all steel parts having an ultimate tensile strength of 150,000 pounds per square inch (psi) and above, which are machined, ground, cold formed or cold straightened, after heat treatment, shall be baked at a minimum of $375^{o}F \pm 25^{o}F$ ($191^{o}C \pm 14^{o}C$) for three hours prior to cleaning and plating for the relief of damaging residual tensile stresses (see 6.2).

3.2.3 Cleaning. Unless otherwise specitied, all steel parts shall be cleaned in accordance with MIL-S-5002 (see 6.2).

3.2.4 Plating Application. Unless otherwise specified, the plating shall be applied after all basis metal heat treatments and mechanical operations, such as machining, brazing, welding, forming, and perforating of the article have been completed (see 6.2).

3.2.5 Underplating. Unless otherwise specified, zinc-nickel alloy shall be deposited directly on the basis metal without a preliminary plating of other metal, such as nickel, or copper, except in the case of parts made of corrosion-resistant alloys on which a preliminary plating of nickel is permissible or of parts made of aluminum on which a preliminary treatment such as the zincate process is permissible (see 6.2).

*3.2.6 Composition. Zinc-nickel alloy plate shall be 6 percent to 20 percent nickel, and the balance shall be zinc.

3.2.7 Coverage. Unless otherwise specified, the plating shall cover all surfaces as stated in 3.3.1, 3.3.1.1, and 3.3.1.2 including roots of threads, corners, and recesses (see 6.2).

*3.2.8 Embrittlement Relief. Unless otherwise specified or stated in the end product specifications, all steel parts having a hardness of Rockewell C40 and higher shall be baked at a minimum of 375°F ± 25°F (191°C ± 14°C) for three hours, within four hours after plating to provide hydrogen embrittlement relief (see 6.5). The baked parts, when tested in accordance with 4.5.4, shall not crack or fail by fracture (see 4.4.3.4). Plated springs and other parts subject to flexure shall not be flexed prior to hydrogen embrittlement relief treatment. In the case of Types II and III treated parts, the baking treatment shall be done prior to the application of the supplementary coatings. Zinc-nickel alloy plated surfaces passivated as a result of the baking operation shall be reactivated prior to receiving the Type II supplementary chromate treatment (see 6.8).

3.2.9 Chromate Treatment (Type II). Unless otherwise specified in the contract or order (see 6.2), the chromate treatment required for conversion to Type II shall be a treatment in or with an aqueous solution of salts, acids, or both, to produce a continuous smooth, distinct protective film, distinctly colored iridescent bronze to brown including olive drab and yellow. The articles so treated shall be thoroughly rinsed and dried in accordance with the requirements of the process used. Type II plating shall be similar in appearance to platings on separate specimens which are capable of passing the salt-spray test (see 3.3.4, 4.4.3.3, and 4.5.3).

3.2.10 Phosphate Treatment (Type III). Unless otherwise specified in the contract or order, the phosphate treatment required for conversion to Type III shall produce a tightly adherent film conforming to Type I of TT-C-490 (see 6.2).

3.3 Detail Requirements.

3.3.1 Thickness of Plating. Unless otherwise specified in the contract order (see 6.2), the thickness of zinc-nickel alloy for other than fastener hardware (see 3.3.1.1) shall be as specified in Table I on all visible surfaces which can be touched by a ball 0.75 inch in diameter. Where Class 1 is specified, all other visible surfaces shall be Class 2 minimum thickness. If the maximum thickness of Class 1 is not specified in the contract, order, or applicable drawing, the thickness shall not exceed 0.001 inch (1.0 mil). Where Class 2 is specified, all other visible surfaces shall be Class 3 minimum thickness. Where Class 3 is specified, all other visible surfaces shall be Class 4 minimum thickness. Where Class 4 is specified, all other visible surfaces shall be not less than 0.00015 inch minimum thickness.

3.3.1.1 For Fastener Hardware. Unless otherwise specified in the end product specifications, fastener hardware shall have Class 3 plating (see 4.5.1 and 6.4). There shall be no bare areas.

3.3.1.2 For Other Than Fastener Hardware. For other than fastener hardware, the zinc-nickel alloy plating shall be Class 3 thickness unless otherwise specified in the contract or order or controlled by the following exceptions (see 6.2):

(a) Articles with portions externally threaded shall have a minimum of Class 3 thickness on the threaded portions.

(b) Holes and other openings and articles with internal threads from which the external environment is completely excluded shall not be subjected to thickness requirements but shall show evidence of coating. There shall be no bare areas.

TABLE I. Thickness.

Class	Thickness	
	Inch Mininum	Equivalent Thickness Micrometers (Approx.) 1/
1	0.0007	18
2	0.0005	13
3	0.0003	8
4	0.0002	5

1/ 0.001 inch = 1 mil = 25.4 micrometers (microns).

3.3.2 Types. Unless otherwise specified in the contract or order (see 6.2), the zinc-nickel alloy plating shall be Type II. For use on surfaces to be painted, the zinc-nickel alloy plating shall be either Type II or Type III (see 6.1.2 and 6.1.3).

3.3.3 Adhesion. The adhesion of the plating shall be such that when examined at a magnification of approximately 4 diameters, the plating shall not show separation from the basis metal or from any underplating at the interface, nor shall any underplate show separation from the basis metal at the interface when subjected to the tests described in 4.5.2. The interface between the plating and either the basis metal or the underplate is the surface before underplating. The formation of cracks in the plating caused by rupture of the basis metal, the underplate or combination of both which do not result in flaking, peeling, or blistering of the plating shall not be considered as nonconformance to this requirement.

3.3.4 Corrosion resistance. Zinc-nickel alloy plating with the Type II treatment shall show neither white corrosion products of zinc-nickel alloy nor basis metal corrosion products at the end of 96 hours when tested by continuous exposure to the salt spray in accordance with 4.5.3. The appearance of corrosion products, visible to the unaided eye at norma' reading distance shall be cause for rejection, except that white corrosion products at the edges of specimens shall not constitute failure.

3.4 Workmanship.

3.4.1 Basis metal. The basis metal shall be free from visible defects that will be detrimental to the appearance or protective value of the plating. The basis metal shall be subject to such cleaning and plating procedures as necessary to yield platings herein specified.

3.4.2 Plating. The zinc-nickel alloy plating shall be smooth, fine grained, adherent, uniform in appearance, free from blisters, pits, nodules, burning, and other defects. The plating shall show no indication of contamination or improper operation of equipment used to produce the zinc-nickel alloy deposit, such as excessively powdered or darkened platings. Superficial staining which has been demonstrated as resulting from rinsing or slight discoloration resulting from any drying or baking operation as specified (see 3.2.8) shall not be cause for rejection. All details of workmanship shall conform to the best practice for quality plating.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection. Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified in the contract or order, the supplier may use his own or any other facilities suitable for the performance of the inspection requirements specified herein, unless disapproved by the Government. The Government reserves the right to perform any of the inspections set forth in the drawing where such inspections are deemed necessary to assure that supplies and services conform to prescribed requirements.

4.2 Classification of inspection. The inspection requirements specified herein are classified as follows:

(a) Production control inspection (see 4.3).
(b) Quality conformance inspection (see 4.4).

4.3 Production control inspection.

4.3.1 Control records. When specified in the contract or order (see 6.2), the supplier shall maintain a record of each processing bath, showing all additional chemicals or treatment solutions to the unit, the results of all analyses performed and the quantity of parts plated during operation. Upon requests of the procuring activity, such records shall be made available. The records shall be maintained for not less than one year after completion of the contract or purchase order.

4.3.2 Production control. The equipment, procedures, and operations employed by a supplier shall be capable of producing high quality electrodeposited zinc-nickel alloy plating on materials as specified in this document. When specified by the procuring activity (see 6.2), the supplier, prior to production, shall demonstrate the capability of the process used to show freedom from hydrogen embrittlement damage as indicated by satisfactory behavior of specimens prepared (see 6.2.2) and tested in accordance with 4.3.2.1 to comply to the requirements of MIL-S-5002 for preproduction process qualification.

4.3.2.1 Preproduction control. For preproduction control four round notched steel specimens shall be prepared in accordance with 4.4.4.3 from four individual heats for a total of 16 specimens, using the specified steel alloy for which preproduction examination of ıe process is to be demonstrated. Specimens shall be heat treated to the maximum tensile rength representing production usage. The specimens shall be given the same pretreatments, ectroplating, and post-plating treatments proposed for production. The specimens shall be ıbject to test detailed in 4.5.4. The process shall be considered satisfactory if all specimens ıow no indication of cracks or failure. The tests results and production control information ıall be submitted to the procuring activity for approval. Until approval has been received, ırts shall be plated.

4.3.3 Frequency of tests. To assure continuous control of the process as required by IIL-S-5002 and to prevent detrimental hydrogen embrittlement during production, the satisfac- ıry behavior of specimens, prepared and tested in accordance with Table II, shall be made nce each month or more frequently if required by the procuring activity. The results of ısts made to determine conformance of electrodeposited platings to all requirements of this rawing for definite contracts or purchase order are acceptable as evidence of the properties eing obtained with the equipment and procedures employed.

4.3.4 Production control specimens. Test specimens for production control shall be repared in accordance with 4.4.4, 4.4.4.1, and 4.4.4.2 as applicable for the thickness, adhe- on, and corrosion resistance tests detailed in Table II. Specimens for the production control mbrittlement relief test shall be four round notched steel specimens of alloy steel 4340 con- ırming to QQ-S-624, heat treated to the maximum tensile strength, from one or more heats, nd prepared in accordance with 4.4.4.3.

TABLE II. Production Control Tests and Specimens.

Test	For Coating Types	Requirement Paragraph	Specimen Preparation Paragraphs	Test Reference Paragraphs
Thickness	I, II, III	3.1.1, 3.3.1.1, and 3.3.1.2	4.4.4 and 4.4.4.1 1/	4.5.1
Adhesion	I, II, III	3.3.3	4.4.4 and 4.4.4.1 1/	4.5.2
Corrosion Resistance	II	3.3.4	4.4.4 and 4.4.4.2 1/	4.5.3
Hydrogen Embrittlement	I, II, III	3.2.8	4.3.4, 4.4.4, and 4.4.4.3	4.5.4

1/ Standard alloy steels shall be used for production control specimens. The selection shall be at the option of the supplier; however, alloy steels such as AISI or SAE number 4130, 4135, 4140, 4145, 4340, 8645, and 8740 conforming to QQ-S-624 shall be used.

4.4 Quality conformance inspection.

4.4.1 Lot. A lot shall consist of plated articles of the same basis metal composition, lass, and type plated and treated under the same conditions and approximately the same size nd shape submitted for inspection at one time.

4.4.2 Sampling for visual examination and nondestructive tests. Sampling for visual xamination and nondestructive tests shall be conducted at the option of the supplier in accor- ance with MIL-STD-105 or using Table III. A sample of coated parts or articles, except for those barrel plated, shall be drawn by taking a random from each lot the number of articles in accordance with MIL-STD-105, Level II, Acceptable Quality Level (AQL) 1.5 percent defective, or as indicated in Table III. Barrel plated parts or articles shall be sampled in accordance with Level S-3 of MIL-STD-105, AQL 4.0 percent defective. The lot shall be accepted or rejected according to the procedures in 4.4.2.1 for visual examination and 4.4.2.2 for plating thickness (nondestructive tests).

TABLE III. Sampling for visual examination and nondestructive tests.

Number of items in lot inspections	Number of items in samples (randomly selected)	Acceptance number (maximum number of sample items nonconforming to any test)
15 or less	7 1/	0
16 to 40	10	0
40 to 110	15	0
111 to 300	25	1
301 to 500	35	1
501 and over	50	2

1/ If the number of items in the inspection lot is less than 7, the number of items in the sample shall equal the number of items in the inspection lot.

4.4.2.1 Visual examination. Samples selected in accordance with 4.4.2 shall be examined for compliance with requirements of 3.4.2 after plating. If the number of nonconforming articles exceeds the acceptance number for the sample, the lot represented by the sample shall be rejected.

4.4.2.2 Thickness of plating (nondestructive tests). Samples selected in accordance with 4.4.2 shall be inspected and the plating thickness measured by the applicable tests detailed in 4.5.1, at several locations on each article as defined in 3.3.1, 3.3.1.1, or 3.3.1.2, as applicable, for compliance with the requirements. Measurements on fastener hardware (see 3.3.1.1) shall be made at locations defined in MIL-STD-1312, Test 12. The part or article shall be considered nonconforming if one or more measurements fail to meet the specified minimum thickness. If the number of defective items in any sample exceeds the acceptance number for the specified sample, the lot represented by the sample shall be rejected. Separate specimens (see 4.4.4.1) shall not be used for thickness measurements unless a need has been demonstrated.

4.4.3 Sampling for destructive tests. A random sample of four plated parts or articles shall be taken from each lot for each destructive test or separately plated specimens shall be prepared in accordance with 4.4.4, 4.4.4.1, 4.4.4.2, and 4.4.4.3 to represent each lot. If the number of articles in the lot is four or less, the number of articles in the sample shall be specified by the procuring activity (see 6.2).

4.4.3.1 Thickness of plating (destructive tests). If sampling and testing for thickness of plating by nondestructive testing is not the option of the supplier, samples selected in accordance with 4.4.3 shall be measured for plating thickness by the applicable test detailed in 4.5.1 at several locations on each article as defined in 3.3.1, 3.3.1.1, or 3.3.1.2 for compliance with the requirements. Measurements on fastener hardware (see 3.3.1.1) shall be made at locations defined in MIL-STD-1312, Test 12. If the plating thickness at any place on any article or specimen is less than the specified minimum thickness, the lot shall be rejected. Separate specimens (see 4.4.4.1) shall not be used for thickness measurements unless a need has been demonstrated.

4.4.3.2 Adhesion (destructive tests). The articles or specimens used for the destructive thickness test (see 4.4.3.1), if of suitable size and form, may be used as the test pieces for the adhesion test to determine compliance with the requirements of 3.3.3. Failure of one or more of the test pieces shall constitute failure of the lot.

4.4.3.3 Corrosion resistance (destructive tests). When specified in the contract or order, compliance with the requirements for corrosion resistance of Type II treated articles shall be determined (see 6.2). A set of four separate test specimens, prepared in accordance with 4.4.4 and 4.4.4.2 in lieu of the treated coated articles shall be used to determine compliance with the requirements for corrosion resistance (see 3.3.4). Failure of one or more of the test specimens shall reject the lot.

4.4.3.4 Hydrogen embrittlement relief (destructive tests). When specified in the contract or order, conformance to the requirements of 3.2.8 for hydrogen embrittlement relief of treated parts shall be determined for those parts which will be subject to a sustained tensile load in use (see 6.2). A random sample of four plated articles shall be taken from each lot of four specimens, prepared in accordance with 4.4.4 and 4.4.4.3, shall be used to represent the lot. When tested as specified in 4.5.4, cracks or failure by fracture shall be cause for rejection. Failure of one or more of the test pieces shall reject the lot.

4.4.4 Quality conformance specimen preparation. When the plated articles are of such form, shape, size, and value as to prohibit use thereof, or are not readily adaptable to a test specified herein, or when destructive tests of small lot sizes are required the test shall be made by the use of separate specimens plated concurrently with the articles represented. The separate specimens shall be of a basis metal equivalent to that of the articles represented. "Equivalent" basis metal includes chemical composition, grade, condition, and finish of surface prior to plating. For example, a cold-rolled steel surface should not be used to represent a hot-rolled steel surface. Due to the impracticality of forging or casting separate test specimens, hot-rolled steel specimens may be used to represent forged and cast-steel articles. The separate specimens may be also cut from scrap castings when ferrous alloy castings are being plated. These separate specimens shall be introduced into a lot at regular intervals prior to the cleaning operations, preliminary plating, and shall not be separated therefrom until after completion of plating. Conditions affecting the plating of specimens including the spacing and plating media, bath agitation, temperature, etc., in respect to other objects being plated shall correspond as nearly as possible to those affecting the significant surfaces of the articles represented. Separate specimens shall not be used for thickness measurements, however, unless the necessity for their use has bene demonstrated.

4.4.4.1 Specimens for thickness and adhesion tests. If separate specimens for thickness and adhesion tests are required, they shall be strips approximately 1 inch wide, 4 inches long, and 0.04 inch thick.

4.4.4.2 Specimens for corrosion resistance tests. If separate specimens for corrosion resistance test are required, they shall be panels not less than 6 inches in length, 4 inches in width and approximately 0.04 inch thick.

4.4.4.3 Specimens for embrittlement relief. Separate specimens for embrittlement relief test shall be round notched specimens with the axis of the specimen (load direction) perpendicular to the short transverse grain flow direction. The configuration shall be in accordance with Figure 8 of ASTM E8 for rounded specimens. Specimens shall have a 60^{o} V-notch located approximately at the center of the gage length. The cross section area at the root of the vee shall be approximately equal to half the area of the full cross section area of the specimen's reduced section. The vee shall have 0.010 ± 0.0005 radius of curvature at the base of the notch (see 6.2.2).

4.5 Tests.

4.5.1 Thickness. For nondestructive measuring of plating thickness, procedures in accordance with FED-STD-151, Method 520 (electronic test), ASTM B499 (magnetic test), ASTM B529 (eddy current), ASTM B567 (test by beta radiation back scatter principle), or ASTM B568 (X-ray spectrometry) may be used. For destructive measuring of plating thickness procedures in accordance with ASTM B487 (microscopic) or ASTM B504 (Coulometric) may be used. In addition to the above, the other procedures embodied in MIL-STD-1312, Test 12, may be used for thickness measurement of plating fastener hardware. Thickness measurements of zinc-nickel alloy platings, Types II and III, shall be made after application of the supplementary treatments. When the coulometric test is used, the supplementary treatment shall be removed prior to testing. The chromate film may be removed from Type II coating by using a very mild abrasive (a paste of levigated alumina rubbed on with the finger). The phosphate coating may be removed from the Type III coating by immersing the specimen in a 10 percent solution of NaOH and scrubbing with a rubber policemen (usually takes from 10 to 15 minutes).

4.5.2 Adhesion. Adhesion may be determined by scraping the surface or shearing with a sharp edge, knife, or razor through the plating down to the basis metal and examining at four diameters magnification for evidence of nonadhesion. Alternately, the article or specimen may be clamped in a vise and the projecting portion bent back and forth until rupture occurs. If the edge of the ruptured plating can be peeled back or if separation between the plating and basis metal can be seen at the point of rupture when examined at four diameters magnification, adhesion is not satisfactory.

4.5.3 Corrosion resistance. Corrosion resistance shall be conducted in accordance with ASTM B117 (salt spray test) for 96 hours or in accordance with MIL-STD-1312, Test 1, for fastener hardware. To secure uniformity of results, Type II supplementary coatings shall be aged at room temperature for 24 hours before subjection to the salt spray.

4.5.4 Embrittlement relief. Compliance with 3.2.8 shall be determined with samples of plated parts taken as specified in 4.4.3.4. Parts such as spring pins, lock-rings, etc., which are installed in holes or rods shall be similarly assembled usign the applicable parts specifications or drawing tolerances which impose the maximum sustained tensile load on the plated part. The selected samples shall be subjected to a sustained tensile load equal to 115 percent of the maximum design yield load for which the part was designed. Fastener hardware, where the maximum design yield load is not known or given, shall be tested in accordance with MIL-STD-1312, Test 5. Parts requirements, or where the maximum design yield load is not known, may be represented by separate specimens prepared in accordance with 4.4.4.3. The notched specimens shall be subject to a sustained tensile load equal to 75 percent of the ultimate notch tensile strength of the material. The articles, parts, or specimens shall be held under load for at least 200 hours and then examined for cracks or fracture.

5. PREPARATION FOR DELIVERY

5.1 Packaging and packing. Preservation, packaging, and packing methods for electrodeposited zinc-nickel alloy plated parts or articles employed by a supplier shall be such as to preclude damaging during shipment and handling.

6. NOTES

6.1 Intended use.

6.1.1 Use. The electrodeposited zinc-nickel alloy platings covered by this drawing are intended for use as corrosion protective platings on ferrous and other basis metal parts. On ferrous parts heat treated or having an ultimate strength between 180,000 to 240,000 psi, zinc-nickel alloy deposition by electrodeposition is not recommended.

6.1.2 Type II treatment. The prime purpose of chromate finishes (Type II) on electrodeposited zinc-nickel alloy platings is to retard or prevent the formation of white corrosion products on surfaces exposed to stagnant water, high humidity atmospheres, salt water, marine atmospheres or cyclic condensation and drying. Some types of chromate coatings have proved satisfactory as a base for paints.

6.1.3 Type III treatment. The prime purpose of phosphate finishes (Type III) on electrodeposited zinc-nickel alloy platings is to form a paint base.

6.2 Ordering data. Purchasers should select the preferred options permitted herein and include the following information in procurement documents:

(a) Title, number, and date of this drawing.
(b) Class and Type required (see 1.1.1, 1.1.2, and 3.3.2).
(c) When plating is to be applied, if other than specified (see 3.2.1, 3.2.4, and 3.2.7).
(d) Stress relief treatment, if other than specified (see 3.2.2).
(e) Cleaning of steel, if other than specified (see 3.2.3).
(f) Underplating required (see 3.2.5).
(g) Luster required, if other than specified (see 3.2.7).
(h) Hydrogen embrittlement relief treatment, if other than specified (see 3.2.8).
(i) Type of chromate treatment required for conversion to Type II, if other than specified (see 3.2.9).
(j) Type of phosphate treatment required for conversion to Type III, if other than specified (see 3.2.10).
(k) Thickness of coating, if other than specified (see 3.3.1, 3.3.1.1, and 3.3.1.2).
(l) Control record requirement (see 4.3.1).
(m) Preproduction control examination (see 4.3.2).
(n) Number of samples for destructive testing (see 4.4.3).

(o) Whether corrosion resistance test is required (see 4.4.3.3).
(p) Whether hydrogen embrittlement relief test is required (see 4.4.3.4).

6.2.1 The manufacturer of the basis metal parts should provide the plating facility with the following data:

(a) Hardness of steel parts (see 3.2.1).
(b) Heat treatment for stress relief, whether it has been performed or is required (see 3.2.2).
(c) Tensile loads required for embrittlement relief test, if applicable (see 4.5.4).

6.2.2 The manufacturer of the basis metal parts should provide the plating facility with notched tensile specimens (see 4.4.4.3) to be plated for conformance with 3.2.8 required for production control (see 4.3.2.1, and 4.3.4) and lot acceptance (see 4.4.3 and 4.4.3.4).

6.3 Stress relief. There is a hazard that hardened and tempered cold-worked or cold-straightened steel parts may crack during cleaning and plating. Such parts should have a suitable heat treatment for stress relief prior to cleaning and plating (see 3.2.2).

6.4 Threaded parts. As heavier platings are required for satisfactory corrosion resistance than class 3 for military use, allowance should be made in the manufacture of most threaded articles, such as nuts, bolts, and similar fasteners with complementary threads for dimensional tolerances to obtain necessary coating build-up. Certain recessed areas, such as root diameters of threads, have a tendency to exhibit a buildup with electrodeposited platings of zinc-nickel alloy.

6.5 Type II temperature limitations. Chromate treatments (Type II) should not be used on plated parts that will not be painted and which will be continuously exposed to temperatures in excess of 150°F (66°C) or intermittently exposed for short periods to temperatures of approximately 300°F (131°C) or more. However, these treatments may be used to prevent finger making and corrosion which may occur at room temperature during assembly and storage.

6.6 Type II handling precaution. Chromate treatments (Type II), which involve only dipping in chemical solutions, normally require a sufficient period of drying, approximately 24 hours at 70°F to 90°F (21°C to 32°C) to render the parts suitable for handling without damage to the coating while in gelatinous forms; and it is important which such coatings that the workmanship be such that the coating is not excessively damaged while wet.

6.7 Reactivation. Surfaces of zinc-nickel alloy plating intended for conversion to Type II and which have become passive as a result of the baking operation specified in 3.2.8 may be reactivated by brief immersion in dilute acid. If, for example, the chromating solution is acidified with sulfuric acid, then the reactivating solution should be one part sulfuric acid (sp. gr. 1.83) by volume added to 99 parts water, or for further example, if the chromating solution is acidified with hydrochloric acid, then the activating solution should be one part hydrochloric acid (sp. gr. 1.16) by volume added to 99 parts water. The duration of immersion should be as brief as is consistent with the nature of the work. For example, a perforated container of barrel-plated parts would be expected to be reactivated in approximately 15 seconds and separately racked items in approximately five seconds. The surfaces should be activated as soon as possible following baking operation and should be handled carefully to avoid contamination by dirt or grease.

10. SCOPE

10.1 Scope. This appendix details the recommended procedure to determine the analysis of the zinc-nickel alloy deposit using one inch square 4130 or 1020 steel panels (0.040 inch thick to 0.0100 inch thick). This appendix is not a mandatory part of the specification. The information contained herein is intended for guidance only.

20 APPLICABLE DOCUMENTS

This section is applicable to this appendix.

30. DEPOSITION ANALYSIS

30.1 Test panel preparation. Remove all scale, dirt, oils, and oxides prior to plating. Deposit 0.0003 inch thick to 0.0007 inch thick plating on the panel.

30.2 Analytical procedure.

30.2.1 Reagents required:

(a) Hydrochloric acid (HCL) - concentrated, reagent grade.

(b) Ammonium hydroxide (NH_4OH) - concentrated, reagent grade.

(c) Indicator, Monohydrate Murexide - One gram dry powder mixed with 100 grams dry sodium chloride (NaCl).

(d) EDTA solution (0.0575 M) - Dissolve 21.4 grams of EDTA (disodium dihydrate salt) in 500 ml of deionized or distilled water and dilute to 1000 ml in a volumetric flask.

(e) Dimethylglyoxime (10 grams per liter solution in ethanol).

30.2.2 Filtering procedures (recommended).

(a) Crude filtration. Set up a 500 ml Pyrex vacuum flask with a Coors USA 2a A-31 (9.6 cm) filter funnel. Use Whatman #1 qualitative (9.0 cm) filter papers. Two or three crude filtrations will be needed with the filter paper being changed between each filtration. Wash the precipitate with deionized or distilled water (5 ml to 10 ml) prior to disposing of the filter paper. Retain the filtrate and proceed with the fine filtration.

(b) Fine filtration. Set up a 500 ml vacuum flask with a Coors USA 07 Gooch crucible. Use a Whatman GF/C 2.4 cm filter. Process the filtrate three times to assure that all traces of the precipitate have been captured by the filter. Retain the filtrate.

30.2.3 Dissolving of sample. Immerse the plated sample in 10 ml to 15 ml of HCl. When the reaction becomes comparatively subdued, the plating alloy has been dissolved and the substrate is being attacked. Carefully remove the metal from the solution when the reaction rate change has occurred, washing with deionized or distilled water. Dilute the solution to 50 ml to 60 m.

30.2.4 Removal of iron. Add ammonium hydroxide until a pH of 10 to 12 has been reached. Crude and fine filter the solution until the filtrate is clear. Limit wash dilution to 75 ml to 100 ml. The solution may be heated to 200°F to accelerate agglomeration of the precipitate. Discard the filtered precipitate. Retain the filtrate and label it "Solution A". Solution A contains the zinc and nickel composition.

30.2.5 Zinc determination.

(a) Pipette 10 ml of Solution A into a 400 ml flask and dilute to approximately 50 ml with deionized or distilled water.

(b) Add 35 ml to 40 ml of the dimethylglyoxime solution.

(c) Crude and fine filter the nickel precipitate from the solution. Discard the filtered precipitate. Retain the filtrate and label it "Solution B".

(d) Add 4 ml to 6 ml of ammonium hydroxide reagent.

(e) Add a spatula of indicator.

(f) Titrate Solution B with the EDTA solution (purple to blue-green). Document the results in Table I, value Z.

30.2.6 Nickel determination.

(a) Pipette a 10 ml sample from Solution A into a 400 ml flask and dilute to 40 ml to 50 ml with deionized or distilled water.

(b) Add 4 ml to 6 ml of ammonium hydroxide reagent.

(c) Add a spatula of indicator.

(d) Titrate with the EDTA solution (gold to purple). Document results in Table I as combination value T.

TABLE I. Composite calculation.

	Titration value	Multiply by	Result/Total
Zinc	(Z)	65.38	(Z)*
Combination	(T)	-	-
Nickel	(T - Z)	58.70	(T - Z)*
Total	-	-	(Z)* + (T - Z)

$$\text{Percent Zinc} = \frac{(Z)^*}{\text{Total}} \times 100$$

$$\text{Percent Nickel} = \frac{(T-Z)^*}{\text{Total}} \times 100$$

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THE EFFECTS OF CO-MINGLING DISSIMILAR FASTENER COATINGS ON THE CORROSION BEHAVIOR OF STEEL BOLT ASSEMBLIES -
Milton Levy, Brian Placzankis, Richard Brown, Robert Huie, Michael Kane, and George McAllister

Technical Report MTL TR 92-40, July 1992, 158 pp - illus-tables

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Key Words

Corrosion testing
Armor steel
Electroplated coatings

Accelerated corrosion tests were carried out to assess the performance of selected coated fastener assemblies representative of those used in the M1A1 tank and Bradley fighting vehicle (coated grade 8 steel bolts fastened to armor steel and Al 5083 blocks). The coatings tested included the currently used electroplated cadmium and zinc as well as proposed electroplates of Zn-Ni, Zn-Co, Sn-Zn and a zinc phosphate modified polyacrylic acid conversion coating. The effect of co-mingling cadmium with the other coatings in the various assemblies was determined. Salt spray testing was performed in accordance with ASTM B117. In addition salt water immersion tests were performed and continuously monitored by electrochemical potential measurements. Breakaway torque values obtained after completion of either immersion or salt spray tests were correlated with coefficient of friction measurements. Cadmium electroplate exhibited the best corrosion protection for grade 8 steel bolts in salt spray or immersion tests. The zinc-nickel coating was the best overall alternative to cadmium plate. The modified zinc phosphate conversion coating was clearly unacceptable. Co-mingling of cadmium with the other coatings did not create a gulvanic corrosion problem. Loosening of the Zn and Zn alloy coated fasteners will not likely occur when Cd torque values are used.

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