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PHASE TWO

FEBRUARY, 1985

U.S. DEPARTMENT OF TRANSPORTATION

*IN COOPERATION WITH
AVONDALE SHIPYARDS, INC.
NEW ORLEANS, LA 70150*

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FOREWORD

This project constitutes a part of the National Shipbuilding Research Program (NSRP), which is cost-shared between the U.S. Maritime Administration and the U. S. Shipbuilding Industry. This research project entitled "The Effect of Edge Preparation on Coating Life" was divided into two phases. Phase one consisted of a literature survey on the subject, an analysis of its results, and recommendations for a test program. ⁽¹⁾

Phase two involved immersion and salt spray testing of test samples. The edges of the test coupons were prepared as follows:

- o flame cut
- o rounded to 1/8"R, 3/16"R and 1/4"R (3.2, 4.8, and 6.4 mm radii)

ABS grade A steel of 1/4" thick (6.4 mm) was selected for the test program. The size of each test sample was 4" x 12" x 1/4" (102 x 305 x 6.4 mm).

Three (3) different coating systems were evaluated: inorganic zinc (Catha-Coat 304, solvent-based), coal tar epoxy (221 Devtar 5A), and polyamide epoxy MIL-P-24441, all supplied by Devoe Marine. The samples were sandblasted to SP-10 finish by using aluminum oxide. There were two different types of application methods: hand brushing plus airless spraying, and airless spraying only. The testing method included immersion pressure testing (IPT) and salt spray testing (SST).

The project was conducted by Franklin Research Center (FRC), Philadelphia, PA 19103 under a subcontract to Avondale Shipyards, Inc. , New Orleans, LA 70150.

The primary objective of the NSRP is to improve shipbuilding productivity and reduce its costs in order to meet the lower construction differential subsidy rate goals of the Merchant Marine Act of 1970. The project outline approved by the Society of Naval Architects and Marine Engineers' (SNAME) Ship Production Committee was followed closely during the course of this study.

Dr. Leslie W. Sandor, Manager of Materials Technology, FRC, was the Project Manager and Principal Investigator for this project. Mr. John W.

Peart, R & D Program Manager, Avondale Shipyards, Inc. was responsible for the program's technical direction and publication of the report. Program definition and guidance were also provided by the members of SNAME Task Group #023-1 on Surface Preparation Coatings.

Sincere appreciations are extended to Devoe Marine for the free supply of coating systems used in the test program.

EXECUTIVE SUMMARY

This report deals with the results of Phase Two of a project entitled "The Effect of Edge Preparation on Coating Life". Phase Two consisted of a test program developed on the basis of the results obtained during Phase One of the overall program.

The variables tested in Phase Two included

1. Edge radius
2. Coating system
3. Application method
4. Test method

Flame cut edges were used as control samples. Three different edge radii were selected and compared with the coating performance on flame cut or sharp edges. Originally there were four coating systems considered for this test program: two inorganic zinc systems (water-based and solvent-based), coal tar epoxy and polyamide epoxy. The water-based inorganic zinc was eliminated because of its unsatisfactory adhesion to the steel substrate. The two coating application methods comprised hand brushing the edges followed by airless spraying the entire sample surface, and airless spraying only. Immersion pressure and salt spray testing constituted the two corrosion test methods. In all cases the test samples were sandblasted to SP-10 finish prior to the application of the paint systems.

The immersion pressure and salt spray tests were terminated after 5,496 hrs (229 days) and 1,440 hrs (60 days), respectively. Preceding the final examination, the test samples were cleaned in 5% citric acid heated to 180°F (82°C) and rinsed in hot water to remove stains for easier identification of failures. Chipping, blistering and rusting were the primary indications of coating failure.

The best overall coating performance was obtained with samples having 1/8 inch (3.2 mm) edge radius coated with polyamide epoxy applied by airless spraying only. The edge performance of the coating systems decreased with an increase in edge sharpness. Flame cut edges are not recommended for applications which require equal coating performance with flat surfaces.

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TABLE II:	Final Results	b

I. CONCLUSION

On the basis of the results of this test program, the following conclusions can be derived.

1. To obtain a coating performance equal to that on a flat plate surface, a minimum edge radius of 1/8"R (3.2 mm) was required. For the case studied, this would correspond to 0.5t (t = plate thickness).
2. The coating performance decreased with decreasing edge radius. The specific coating life with decreasing edge radii was strongly influenced by the type of coating system employed. In this respect, the best edge performance was obtained with polyamide epoxy, the worst with 304 zinc, and intermediate with the coal tar 5A coating system.
3. The sharper the radius of curvature on an edge, the shorter the life of a specific coating system. Oxyacetylene flame cut edges gave the shortest coating life. The inorganic zinc (304) coating system applied with brushing plus spraying on sharp edges yielded the worst results.
4. Of the two application methods, the brushing followed by airless spraying was considered worse than airless spraying only. The heavy but inconsistent coating thickness built up by hand brushing had a great tendency to chip off and thereby expose the bare steel edges to rusting. This was particularly true with the inorganic zinc, which was the most brittle coating of the three systems studied.
5. In general, the polyamide epoxy coating system was found to give the best edge performance in both the immersion and salt spray tests.
6. Salt spray testing relative to immersion pressure testing had an accelerating effect on failure of the coating systems.

II. PLAN OF ACTION

II.1 Objective

The principal objective of the test phase of this project was to evaluate the edge performance of different coating systems in immersion and salt spray tests.

II.2 Introduction and Background

In Phase I of this project, it was recommended that a test program be initiated to basically validate the findings of a literature search and industry survey with coating systems used in the U.S. shipbuilding industry.

The literature study showed that the edge performance of a given coating system was affected by edge radius, surface preparation, coating thickness as well as integrity, viscosity, and exposure conditions. Consequently, the proposed test program was designed to examine different edge radii, specific edge and surface preparations, various application methods, different coating systems, and different corrosion test methodologies.

II.3 Procedure

ABS (American Bureau of Shipping) grade A steel was chosen for the test program. The sample size was finalized at 4" x 12" x 1/4" (102 mm x 305 mm x 6.4 mm). The control samples had sharp edges prepared by oxyacetylene flame cutting. The edge radii (or radii of curvature) to be tested included 1/8" (3mm), 3/16" (5 mm), and 1/4" (6.4 mm). The edges were prepared to the required radii by machining to ensure consistency in radius of curvature along the edges of the test samples. Then, both the flat surfaces and edges were sandblasted to SP-10 finish by using aluminum oxide particles.

Originally, four (4) different coating systems had been considered; polyamide epoxy, inorganic zinc of both water-based and solvent-based, and coal tar epoxy. Two different application methods were used for coating the edges of the test samples: brushing followed by airless spraying and airless spraying only. The coating thicknesses were built up to those of the manu-

facturer's recommendations for the respective coating systems. The corrosion test methods consisted of immersion pressure testing and salt spray testing. There were three (3) samples per test variable, which meant a total of 192 samples for the test program. The test medium was 3% salt solution. The immersion pressure test involved a 20-day immersion or wet cycle followed by a 10-day dry cycle with a 2" (50.8 mm) salt solution left on the tank bottom, while the tank was constantly pressurized at 15 psi. The durations of the immersion pressure and salt spray tests were 229 days (5,496 hrs) and 60 days (1,440 hrs), respectively. The test temperatures for the immersion pressure and salt spray tests were ambient and 98°F, respectively. All the samples after testing were cleaned in 5% citric acid heated to 180°F (82°C) followed by rinsing in hot running water to reveal sites of coating failure.

III. DISCUSSION OF RESULTS

The reason for choosing 1/4" thick steel plate was to keep the weight of the test samples at a manageable level. The edge radii of 1/8", 3/16", and 1/4"R were selected on the basis of a Russian publication.⁽²⁾ This meant that the 1/8" radius gave a rounded edge on the 1/4" thick steel plate. Since the plate thickness was constant, the increase in the radius of curvature from 1/8"R to 1/4"R resulted in an increase in edge sharpness as can be seen in Fig. 1. So in actuality, the range of edge sharpness varied from the flame cut edge being the sharpest to the fully rounded edge obtained with the 0.5t radius.

After machining the edges to the specific radii, the test samples were sandblasted to SP-10 finish ("white metal"). A few sandblasted samples were randomly selected for surface roughness measurement by a BRUSH SURFACE ANALYSER. Both the edges and flat surfaces showed a surface roughness variation of .001 - .002 inch (.0254 - .0508 mm). The surface conditions before and after sandblasting are shown in Fig. 2-5. Note that in Fig. 5, the flat surface conditions are illustrated only for the flame cut and 1/4"R samples. The photographs for the 3/16"R and 1/8"R did not turn out satisfactorily. The flat surface conditions for these two samples were, however, the same as those for the flame cut and 1/4"R samples.

LEGEND :

- 1 -- Edge radius = 1/8" (or Dia = 1/4")
- 2 -- Edge radius = 3/16" (or Dia = 3/8")
- 3 -- Edge radius = 1/4" (or Dia = 1/2")
- a -- Amount of edge material removed
(a_1 greater than a_2 greater than a_3)
- t -- Plate thickness = 1/4 "

NOTE :

Drawings to full scale

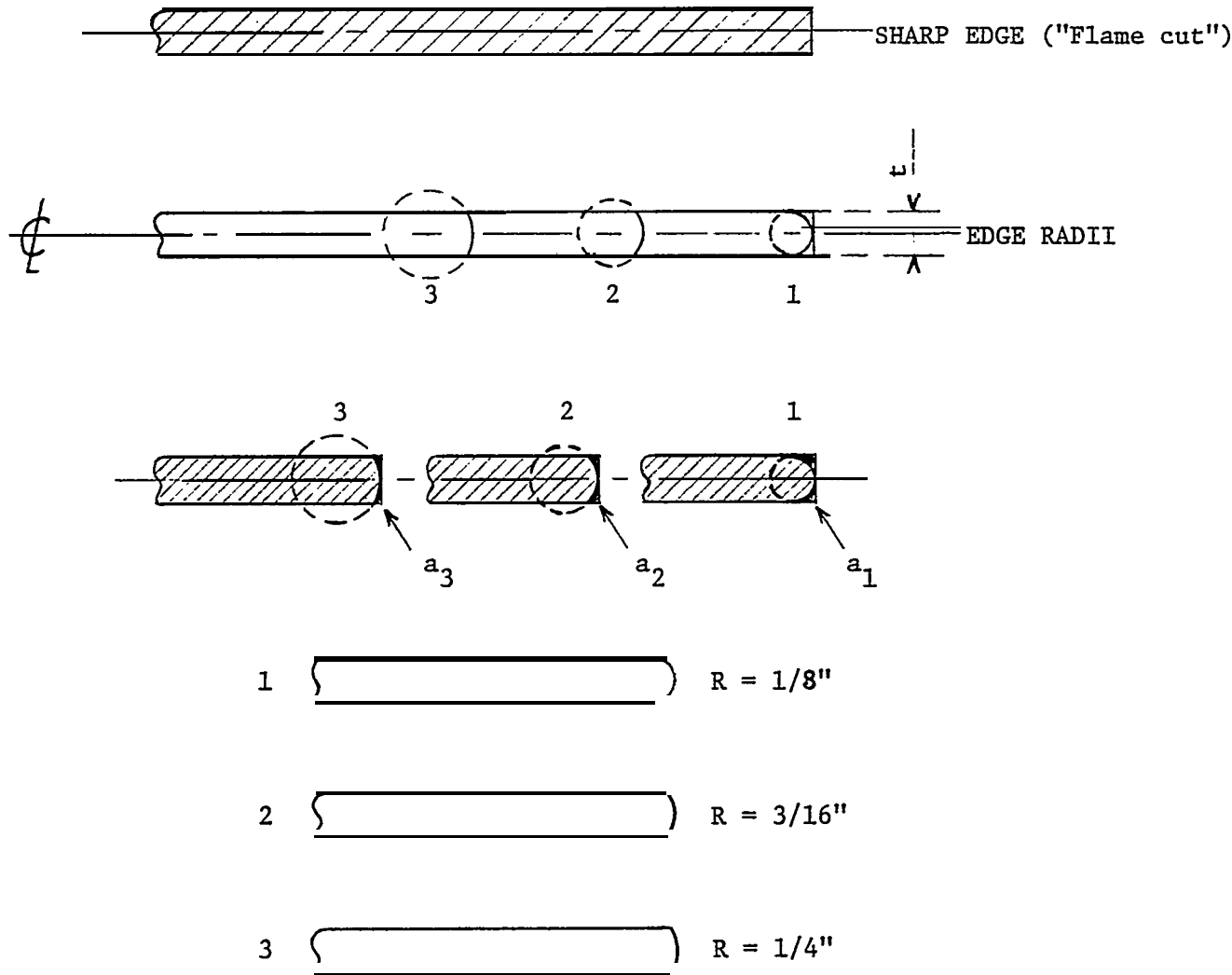


Fig. 1. Illustrations of different edge preparations on 1/4" thick plate.



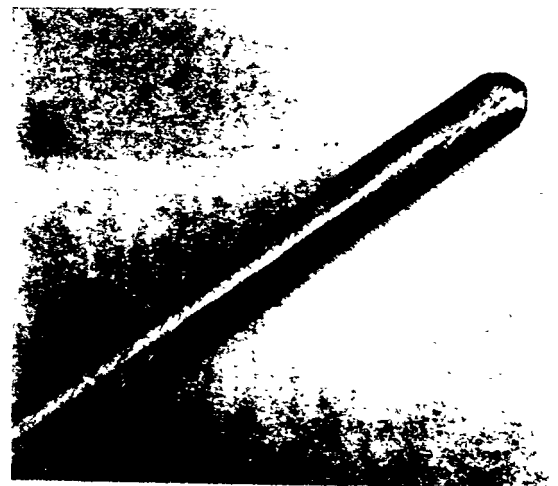
(a)



(b)



(c)



(d)

Fig. 2. Surface condition of edges before sandblasting:
(a) flame cut, (b) 1/4"R, (c) 3/16"R, (d) 1/8"R.



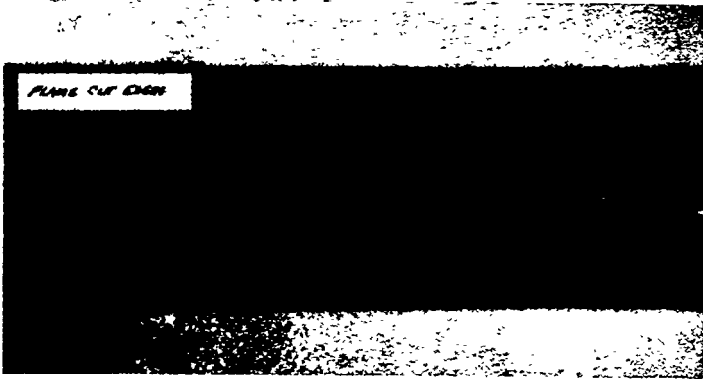
(a)



(c)



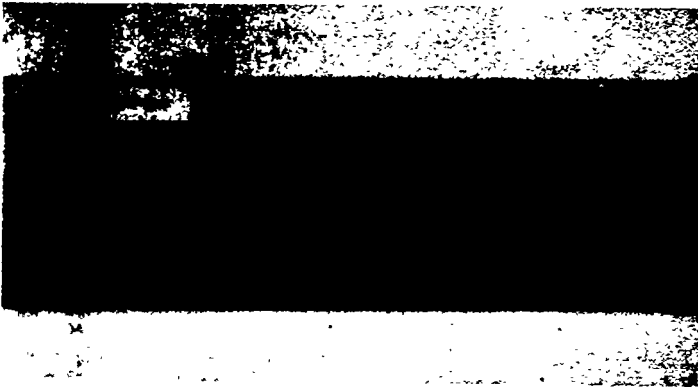
Fig. 3. Surface condition of edges after sandblasting:
(a) flame cut, (b) $1/4''R$, (c) $3/16''R$, (d) $1/8''R$.



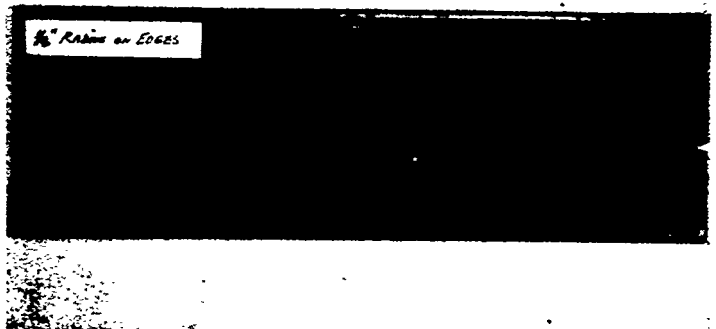
(a)



(b)

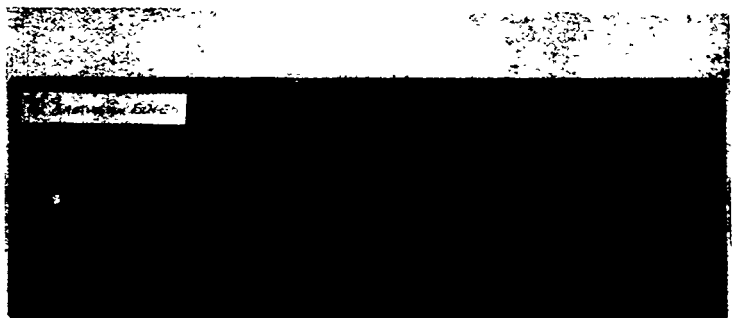
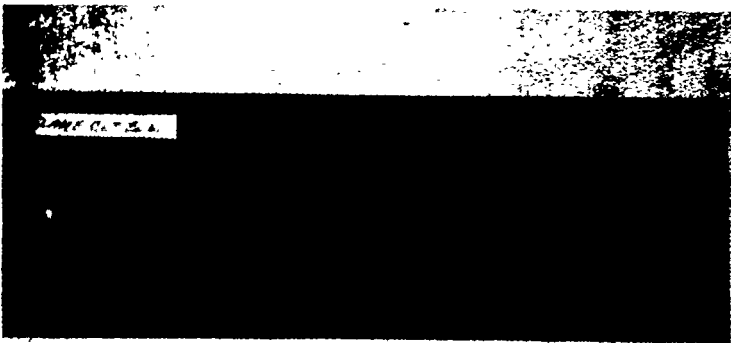


(c)



(d)

Fig. 4. Surface condition of flat surfaces before sandblasting:
(a) flame cut, (b) 1/4"R, (c) 3/16"R, (d) 1/8"R.



(b)

Fig. 5. Surface condition of flat surfaces after sandblasting:
(a) flame cut, (b) 1/4"R.

Painting of the test samples was started immediately after sandblasting. The viscosity of each of the four paint systems was checked prior to application to ensure conformance to manufacturer's specifications. For the application method which involved brushing followed by airless spraying, the coating along the edges was allowed to dry after hand brushing. Then, the entire sample surface (flats and edges) was coated with airless spraying to the thickness recommended by the paint manufacturer. The coating thickness was checked after curing by a gauge at several locations randomly. The coatings were applied at room temperature (about 72°F) under controlled humidity conditions.

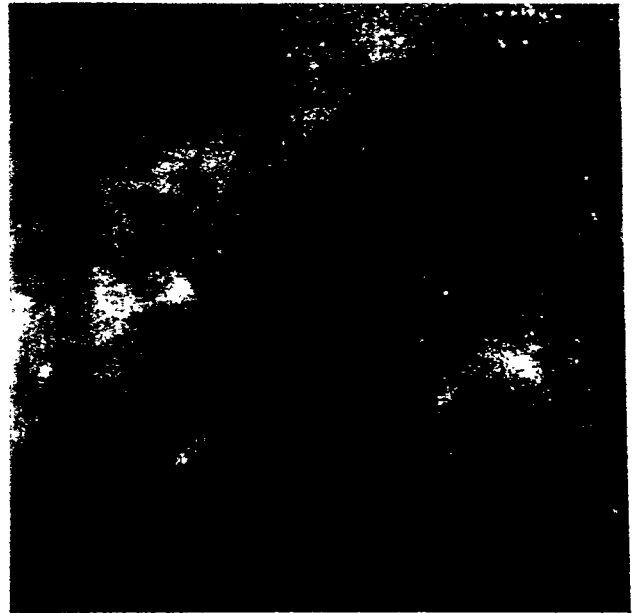
The water-based inorganic zinc coating (Catha-Coat 305) did not adhere to the steel surface, particularly on the edges. This paint would peel or flake off the steel surface sporadically as shown in Fig. 6. Different conditions of brushing and spraying were attempted to solve the flaking problem without success. The surfaces of the steel samples were investigated for possible contamination of grease, oil, or fingerprints. None was found. After decreasing and re-sandblasting the test coupons, the water-based inorganic zinc would still not adhere to the steel surface satisfactorily. Therefore, this coating system was eliminated from the test program. Thus, the total number of samples for the actual test program was decreased from 192 to 144.

The solvent-based inorganic zinc (Catha-Coat 304) coating adhered to the steel surface satisfactorily. Some clogging of the spray gun was noticed initially with Catha-Coat 304, which was corrected subsequently. The coal tar epoxy (221 Devtar 5A) was found to be sensitive to temperature effects and mixing conditions. The polyamide epoxy posed no problem at all.

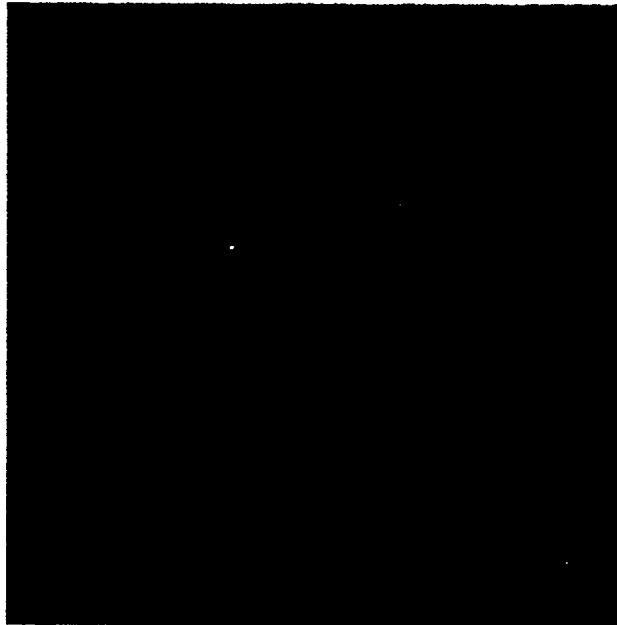
Immersion pressure and salt spray tests were chosen for evaluating the edge performance of the three coating systems. The immersion pressure test was set up to simulate ship conditions to some extent. It consisted of a 20-day wet cycle and a 10-day dry cycle. The immersion test chamber was under a constant air pressure of 15 psi (103.4 kPa). The testing medium in both test methods involved 3% salt solution. After every wet and dry cycle, the samples were inspected for signs of breakdown in the coating systems such as blistering, softening, peeling, undercutting, chipping, pitting and rusting.



(a)



(b)



(c)

Fig. 6. Flaking of the water-based inorganic zinc coating (305) on (a) flame cut, (b) 1/4"R, (c) 1/8"R edges after sandblasting. Paint was applied by hand brushing.

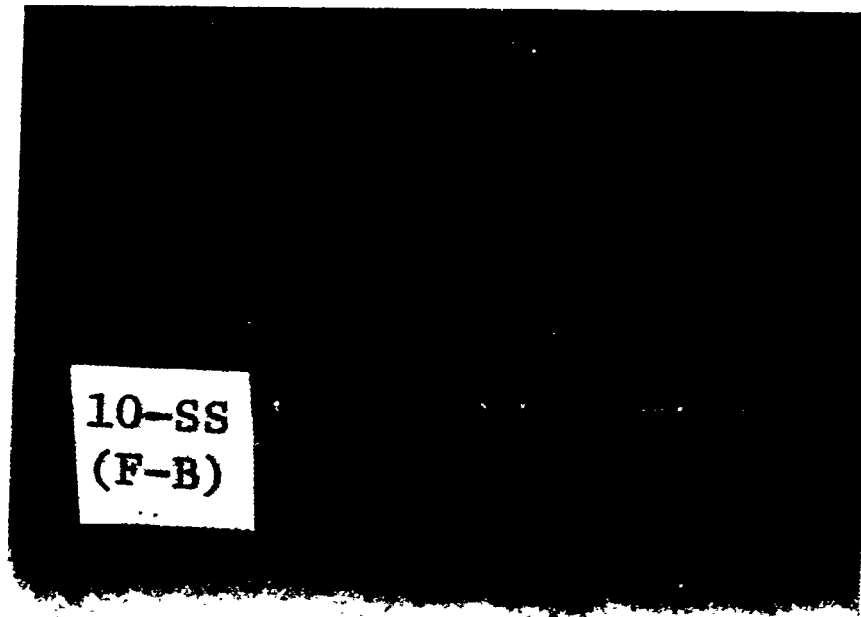
The salt spray test samples were examined periodically for indications of failure in the respective coating systems.

Chipping of the brushed and sprayed coating along flame cut, or sharp edges was the first and primary mode of coating failure, especially with the zinc system. (See Fig. 7-8.) Hand brushing resulted in an unevenly thick paint build up along sharp edges. The inorganic zinc coating (304) is an intrinsically brittle coating. This thick and brittle coating was most susceptible to chipping on flame cut (F) corners as shown in Fig. 7a.

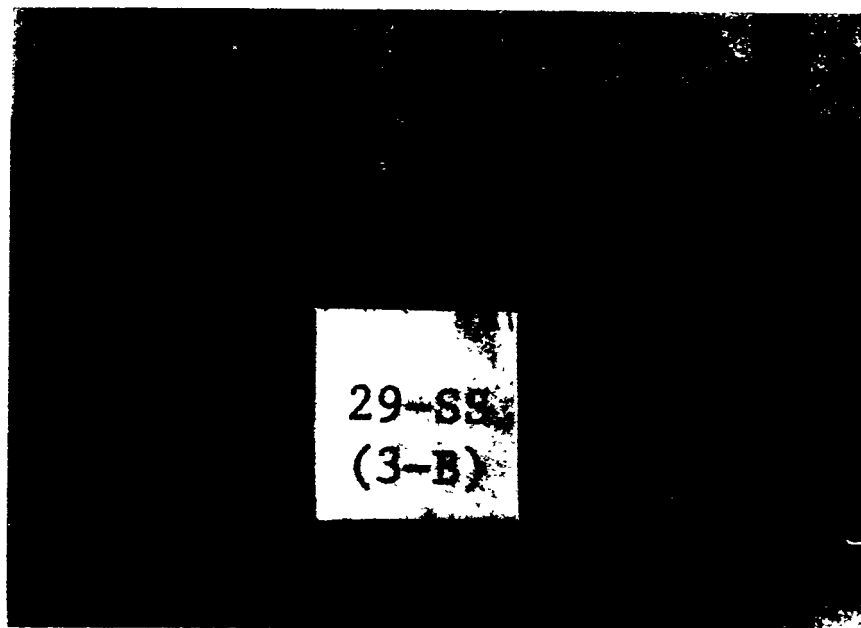
Chipping was frequent on 1/4"R edges (4) as demonstrated in Fig. 8 which shows two different chipped areas on sample No. 27. This sample was exposed to salt spray testing (SS). The chipped off areas of the steel after 1440 hrs of exposure in the salt spray cabinet were completely rusted. Fig. 9 shows rust along a 1/4"R edge of sample No. 39 coated with solvent-based inorganic zinc applied by airless spraying only (S). This sample was exposed to 5496 hrs of immersion pressure testing. Displayed in Fig. 10 is a 1/8"R edge (2) of sample No. 28 brushed and airless sprayed (B) with 304 zinc after 60 days of salt spray testing (SS). The condition of the edge of this sample was as good as that of its flat surface. The general appearance of samples No. 28 and No. 42 after 60 days of salt spray testing is presented in Fig. 11.

While the bare steel over the chipped area is anodically protected by the surrounding zinc coating for some length of time, the extent of anodic protection is a function of the ratio of the two areas. The area of the bare steel exposed by the chipping of the paint system cannot be controlled because of the manual nature of paint brushing, resulting in a random build up of coating along the edges. What makes things even worse for flame cut edges is that such edges are innately very irregular to begin with.

The coal tar epoxy (5A) coating was not as prone to chipping as the inorganic zinc. However, it was susceptible to a blistering problem as its primary failure mechanism. Typical examples of edge failures found in the coal tar system are illustrated in Fig. 12-15. The rust along the flame cut edge of sample No. 97 was 6-1/2" long. Blistering of the paint system was quite evident on samples No. 84 and 76. The excellent performance of 1/8"R edges coated with the coal tar epoxy system is exhibited in Fig. 16.

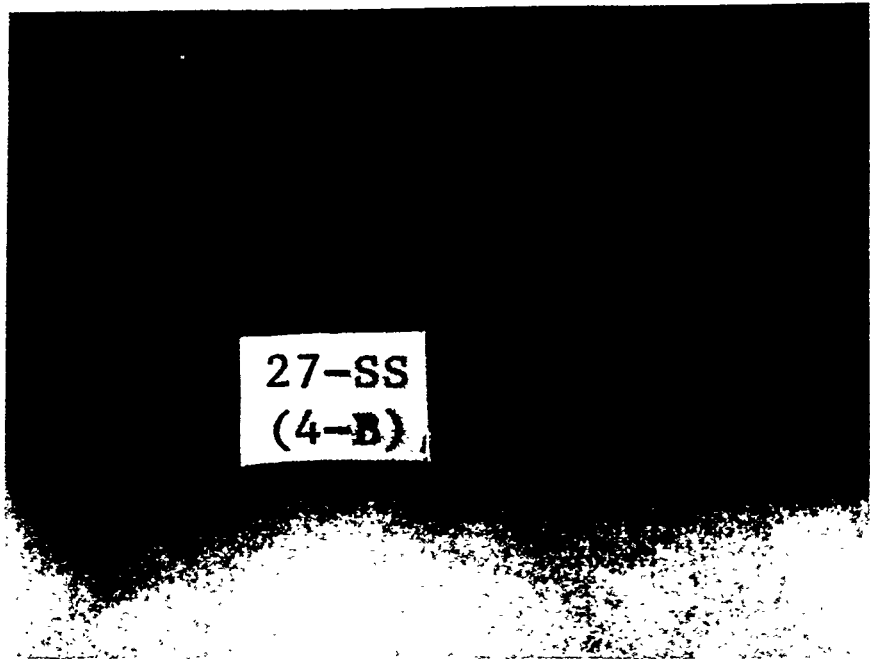


(a)

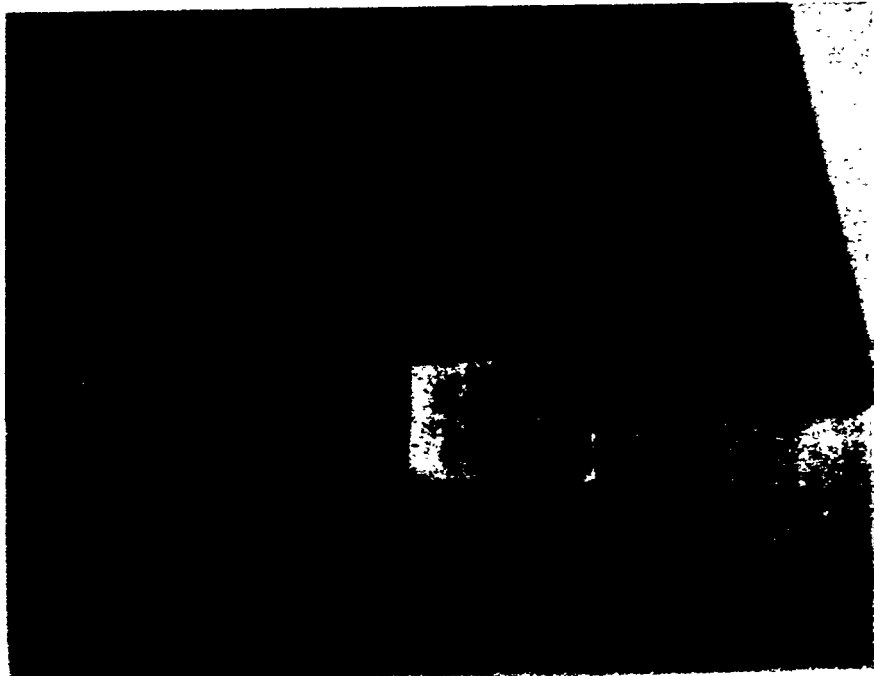


(b)

Fig. 7. Solvent-based inorganic zinc (304) applied by hand brushing followed by airless spraying chipped off along (a) flame cut edge, and (b) 3/16"R edge. Note the rust formed on the chipped off surface (1-1/2" long).



(a)



(b)

Fig. 8. Solvent-based inorganic zinc (304) applied by brushing and spraying (B) shows chipping of the paint on 1/4"R edges (4). Sample No. 27 was tested in salt spray (SS).



Fig. 9. Solvent-based inorganic zinc (304) applied by airless spraying only (S) displays rusting along a 1/4"R edge of sample No. 39 exposed to 5496 hrs of immersion pressure testing.

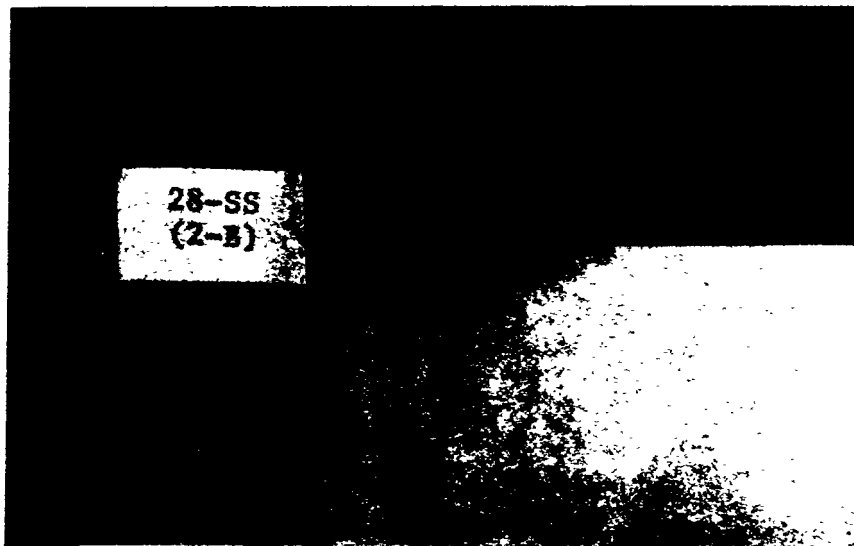


Fig. 10. Sample No. 28 exhibited the same salt spray performance along the 1/8"R edges as it did on its flat surfaces.

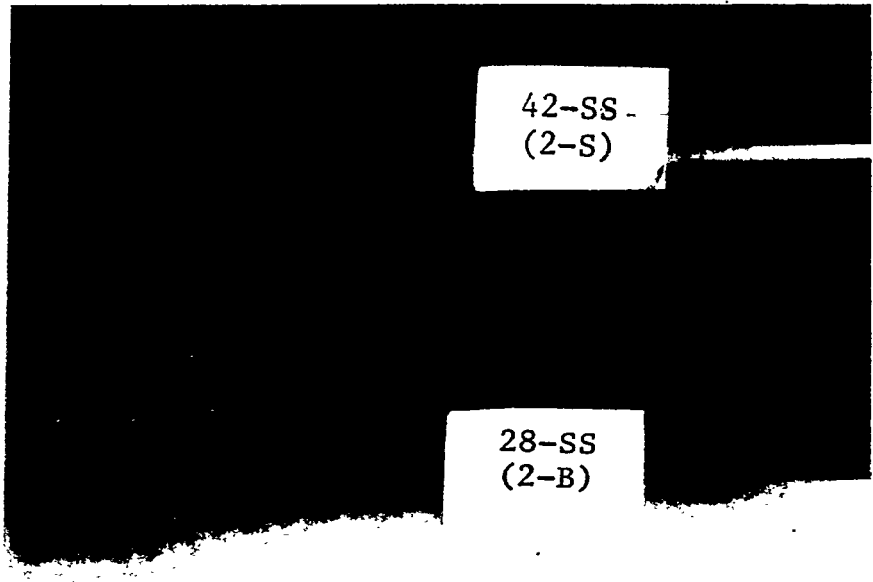
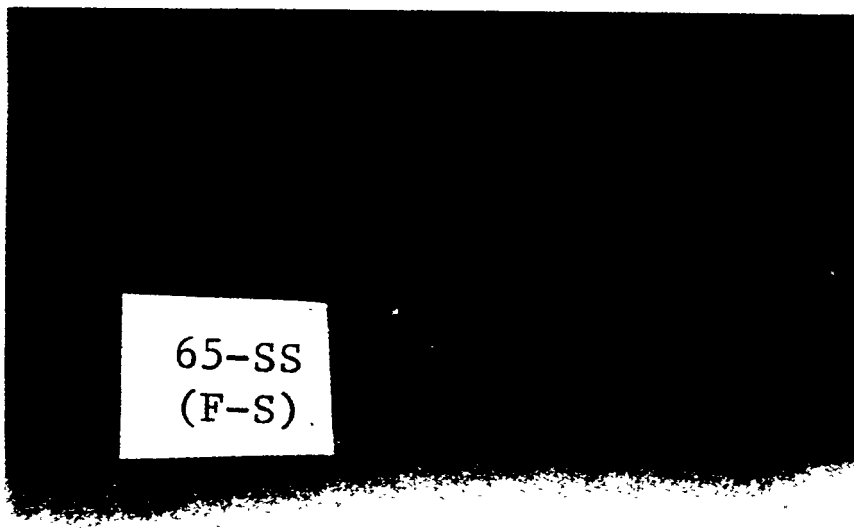


Fig. 11. General appearance of samples No. 28 and No. 42 after 1440 hrs of salt spray testing representing 1/8"R edges and zinc 304 coating system.

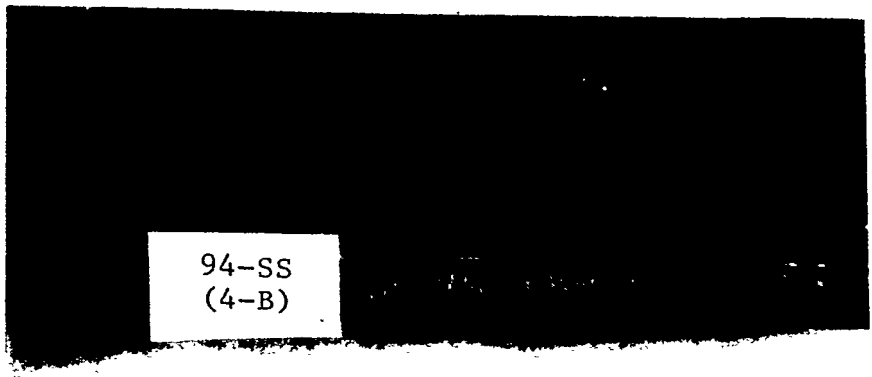


(a)

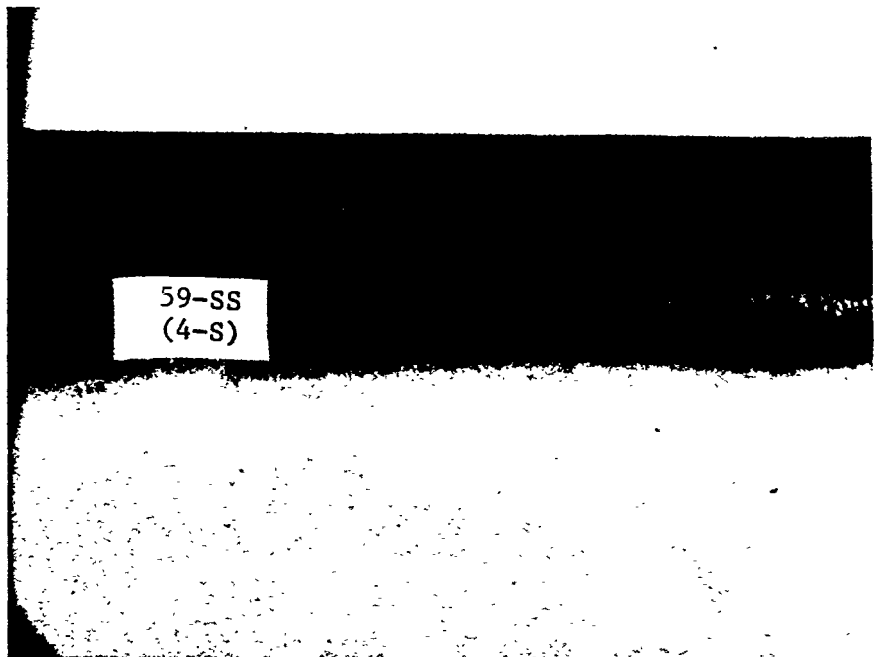


(b)

Fig. 12. Rust formation along flame cut edges (F) of
(a) sample No. 97, brushed and sprayed (B) with coal tar epoxy tested in salt spray
(b) sample No. 65, spray coated (S) with coal tar epoxy tested in salt spray (SS).



(a)

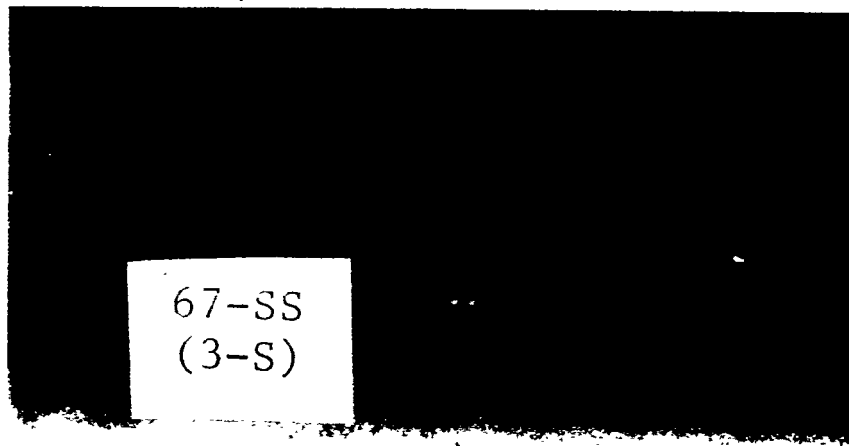


(b)

Fig. 13. Rust formation on 1/4"R edges of samples No. 94 and 59 both coated with coal tar epoxy and tested in SS for 1440 hrs.
(a) application method: brush plus spray
(b) application method: spray only. Length of edge rust: 3".



(a)

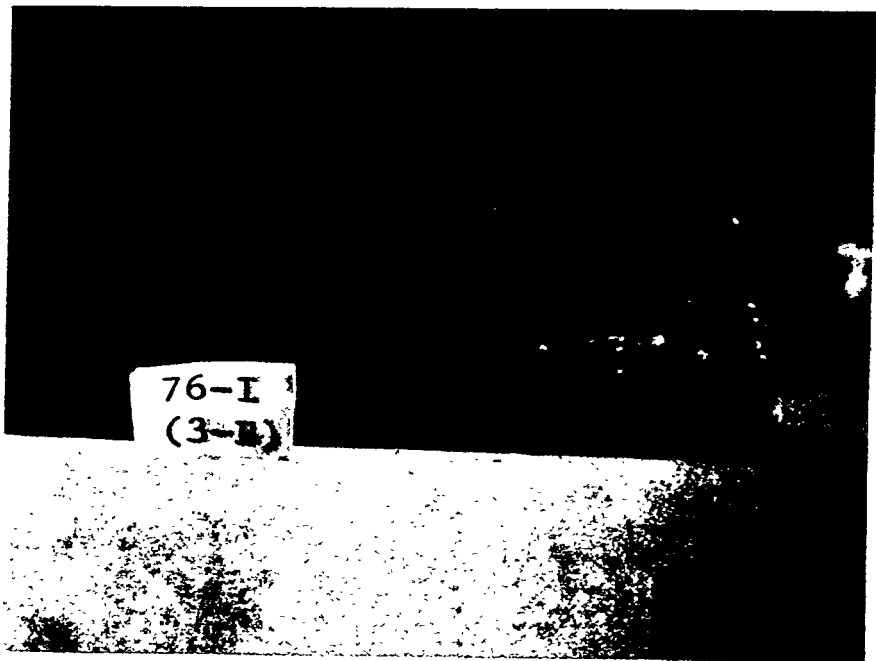


(b)

Fig. 14. Rust formation on 3/16"R edges of samples No. 81 and 67 coated with coal tar epoxy and tested in SS for 60 days.
(a) Brush and spray application method. Length of edge rust: 3-1/2".
(b) Airless spray application method.

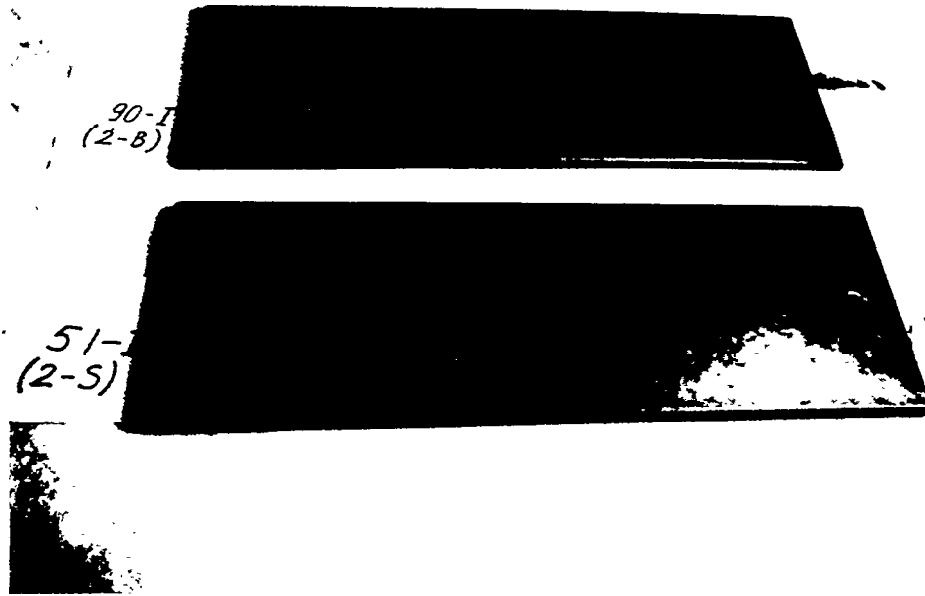


(a)

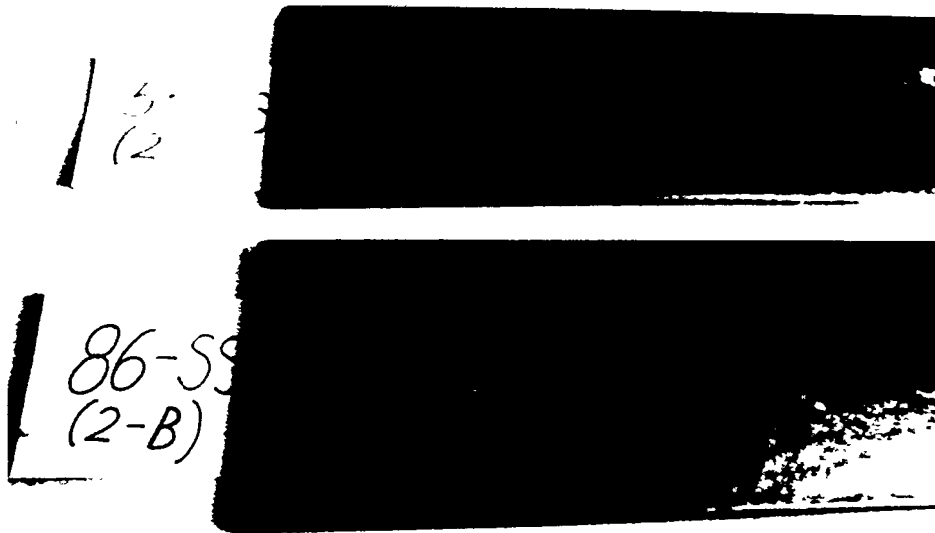


(b)

Fig. 15. Rust formation along flame cut (F) and 3/16"R (3) edges of sample No. 84 and 76 coated with coal tar epoxy and tested in immersion pressure test (I). The coating on both samples was applied by brushing plus airless spraying.



(a)



(b)

Fig. 16. Excellent coating performance of coal tar epoxy on 1/8"R edges.
(a) Immersion pressure test samples after 229 days.
(b) Salt spray test samples after 60 days.

The polyamide epoxy proved to be the best coating system of the three systems tested in this program. Fig. 17 shows two samples immersion pressure tested for 5496 hrs without a sign of coating failure on flame cut edges. Both samples were coated with polyamide epoxy; sample No. 121 with striping and spraying, and sample No. 144 with spraying. Polyamide coated samples with 1/8"R edges seen in Fig. 18 showed no sign of failure of any kind after 229 days of immersion pressure testing, or after 60 days of salt spray testing. The zinc and coal tar systems began to show signs of failure of one kind or another much earlier in both test methods than did the polyamide coating system. In fact, the test program lasted as long as it did because of the excellent performance of the polyamide epoxy. Table I contains the various types of coating failure found on the test samples. Rusting, chipping, and blistering were among the primary indications of coating failure. The immersion pressure test was terminated after 229 days (5,496 hrs) and the salt spray fog test after 60 days (1,440 hrs).

Perhaps the best way to illustrate the relative differences in edge performance of the three coating systems is to discuss the results of flame cut samples after the termination of both the immersion and salt spray tests.

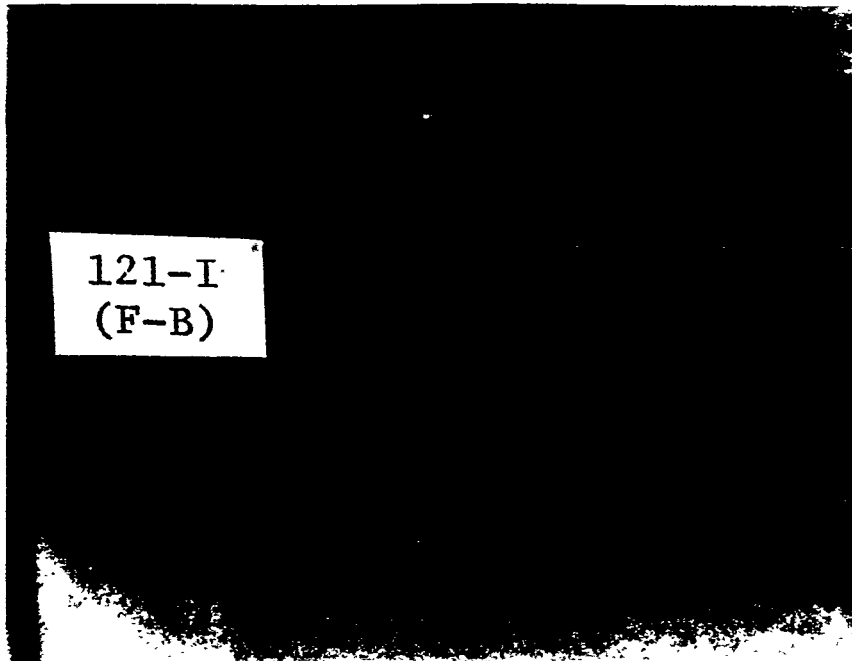
Immersion Test:

- All of the six samples coated with 304 failed (100% failure).
- Five out of six samples coated with 5A failed (83% failure).
- None of the six samples coated with polyamide failed (0% failure).

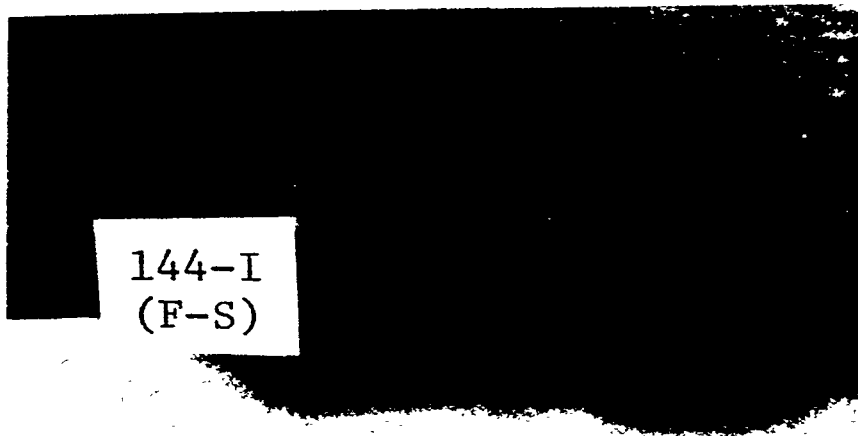
Salt Spray Test:

- All of the six samples coated with 304 failed (100% failure).
- All of the six samples coated with 5A failed (100% failure).
- Two out of the six samples coated with polyamide failed (33% failure).

Furthermore, no failure was noted in the radiused (rounded) samples coated with polyamide after 5496 hrs of immersion testing or 1440 hrs of salt spray testing. The two polyamide samples that indicated failure on flame cut edges had been coated with the airless spray application method. In the case of the radiused samples coated with the zinc and coal tar systems, the samples with

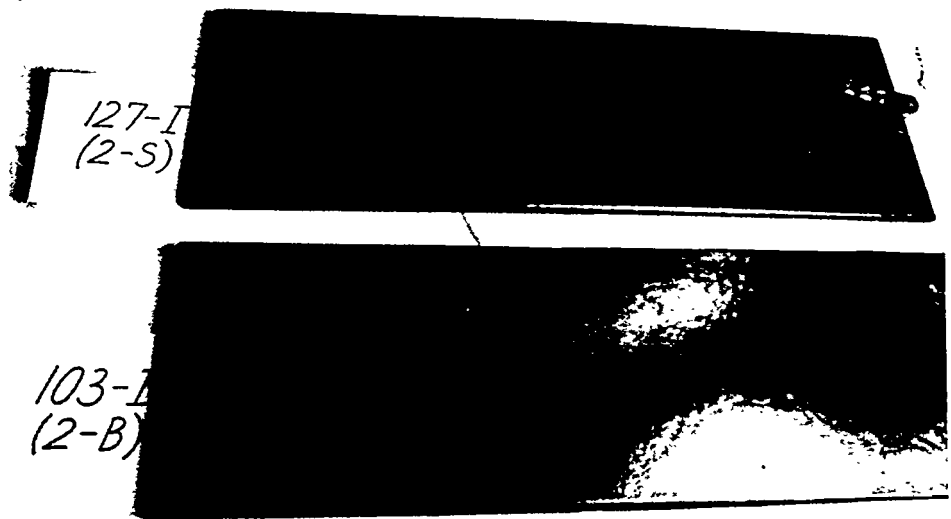


(a)



(b)

Fig. 17. No sign of failure of the polyamide coating system along flame cut edges exposed to immersion pressure testing for 5,496 hrs. Note the "raised effect" of the extra heavy coating on the edge resulting from hand brushing or striping shown in photograph (a).



(a)



(b)

Fig. 18. Polyamide coated samples with 1/8"R edges show excellent performance.

(a) after 229 days in immersion pressure testing.

(b) after 60 days in salt spray testing.

the 1/8"R was the only group that did not show a failure. The other two groups of samples with 3/16"R and 1/4"R edges showed an increasing percentage of failure with increasing sharpness of the edges. (Note that the larger the radius, the sharper the edge since the plate thickness was constant.) It should be pointed out about zinc 304, that this coating system is so brittle that chipping can occur even on 1/8"R edges, particularly when hand brushed. This can come about as a result of, for example, rough handling of the test sample. (See Fig. 19). The final results of this test program are summarized in Table II and plotted in Fig. 20. The coating failure expressed in percent represents the number of samples which showed some sort of coating failure out of a 6-sample lot per edge preparation and application methods combined. It is quite obvious that the fully rounded edge obtained with the 1/8" radius of curvature gave the best results. With these samples, no failures in any one of the three coating systems tested were found after 229 days of immersion pressure testing, or 60 days of salt spray testing. In general, the edge performance of the coating systems decreased as the sharpness of the edge increased. In an overall sense, the airless sprayed samples produced better and more consistent results than the striped and airless sprayed samples. The polyamide coating system out-performed the other two samples by a considerable margin as can be seen in Fig. 20. While there was no failure noted on any of the polyamide coated edges tested in immersion pressure for 229 days, it is expected that an extension of the test period would show the same, inverse relationship between edge radius and coating performance as was the case with the other samples and tests.

The salt spray test method induced failures in the coating systems at a faster rate than did the immersion pressure test. This suggests that the type of environment does have an effect on the life of any given coating system used to prevent corrosion.

The matrix of the test program and the data sheets provided by Devco Marine on its four coating systems (Catha-Coat 304, 305, 21 Devtar 5A, and Polyamide epoxy) are appended to this report.



Fig. 19. Zinc 304 paint chipped off on a 1/8"R edge caused by mishandling of the test sample. (No rust over the chipped off area.)

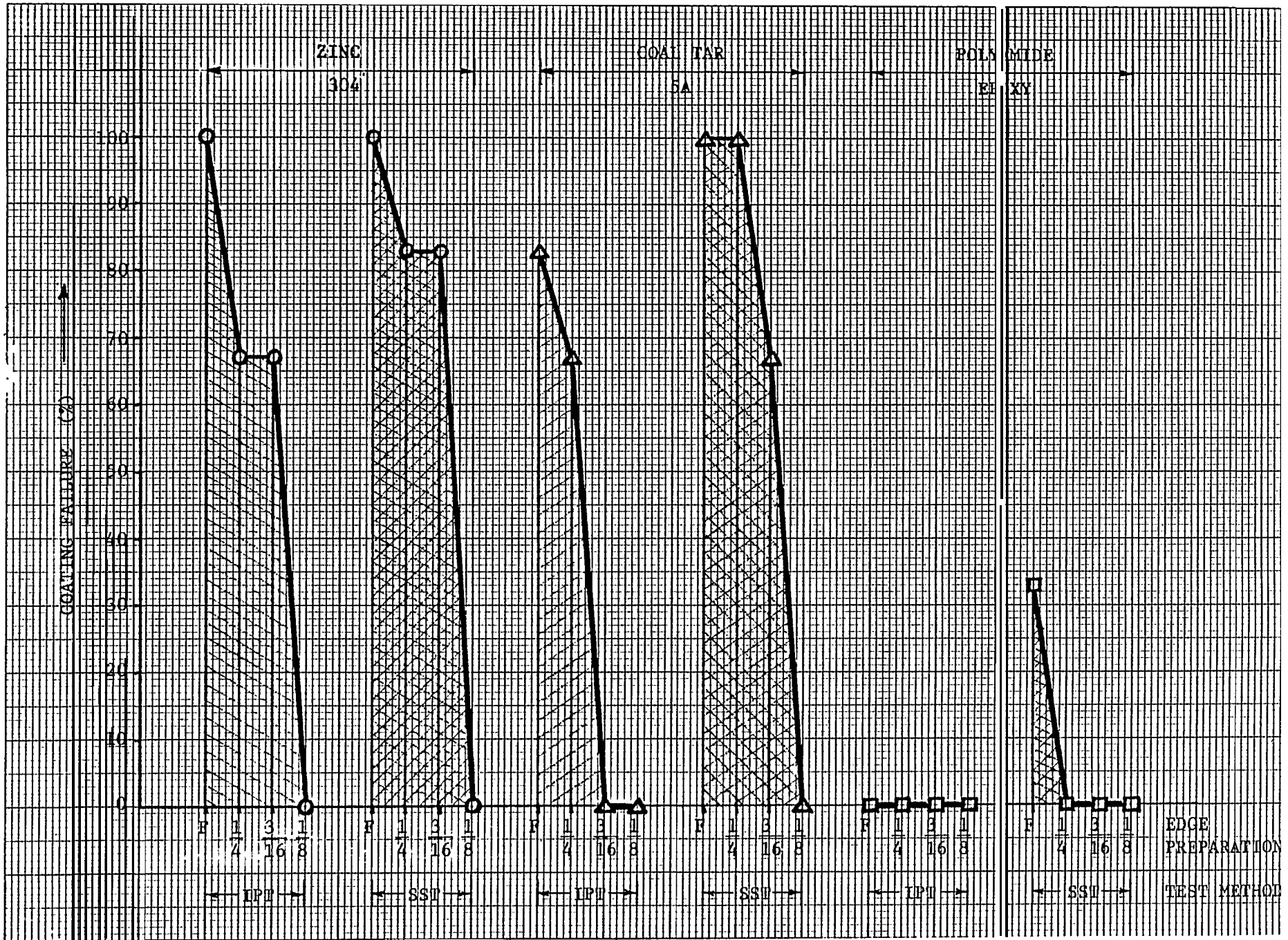


Fig. 20. Final results of the test program.

IV. RECOMMENDATION

The results of this test program suggests the following:

1. Edge preparation of steel plates is highly desirable for situations where the life of a particular coating system along plate edges is required to match that of a flat surface. In this regard, the radius of curvature on a steel plate edge should be $0.5t$, where t equals the plate thickness. The thickness range within which the "0.5t rule" would apply was not defined in this test program. The upper and lower bounds of $0.5t$ should be determined.
2. The 3-5 mm edge radius corresponds to a bevel angle of $135-150^\circ$, according to Kharlamov and Koshin. ⁽²⁾
3. For edge radii under 3 mm (1/8 inch), the life of a particular coating system is expected to decrease as the edge radius decreases. The edge performance of any given coating system is inversely proportional to the sharpness of the edge.
4. The use of a flame cut edge should be avoided with any coating system, when the criterion for whatever reason is to match the coating performance of an edge with that of a flat surface.
5. Brush coating or striping of a sharp edge such as a flame cut edge should be avoided, particularly when the manually applied coating system becomes intrinsically brittle upon curing. Such coatings on sharp edges have a great tendency for chipping.
6. The ranking of the three coating systems in decreasing order of performance is as follows:
 - 6.1 Polyamide - best
 - 6.2 Coal tar - distant second
 - 6.3 Zinc - worst
7. For best protection, the edges of steel plates should be rounded off to a minimum of 3.2 mm (1/8 inch) radius or bevelled to at least 135° and coated with polyamide epoxy applied by airless spraying only.

BIBLIOGRAPHY

1. Sandor, L. W., "The Effect of Edge Preparation on Coating Life," Phase One, U.S. Department of Transportation, Maritime Administration, Avondale Shipyards, Inc., May 1983.
2. Kharlamov, I. V., and Koshin, I. I., "Corrosion Protection of the Members (Elements) of Steel Structures with Different Bevel Angles and Radii of Curvature of the Edges," Izvestiya VUZ, No. 8, pp. 17-22, August, 1976.

ANNEX

TABLE I

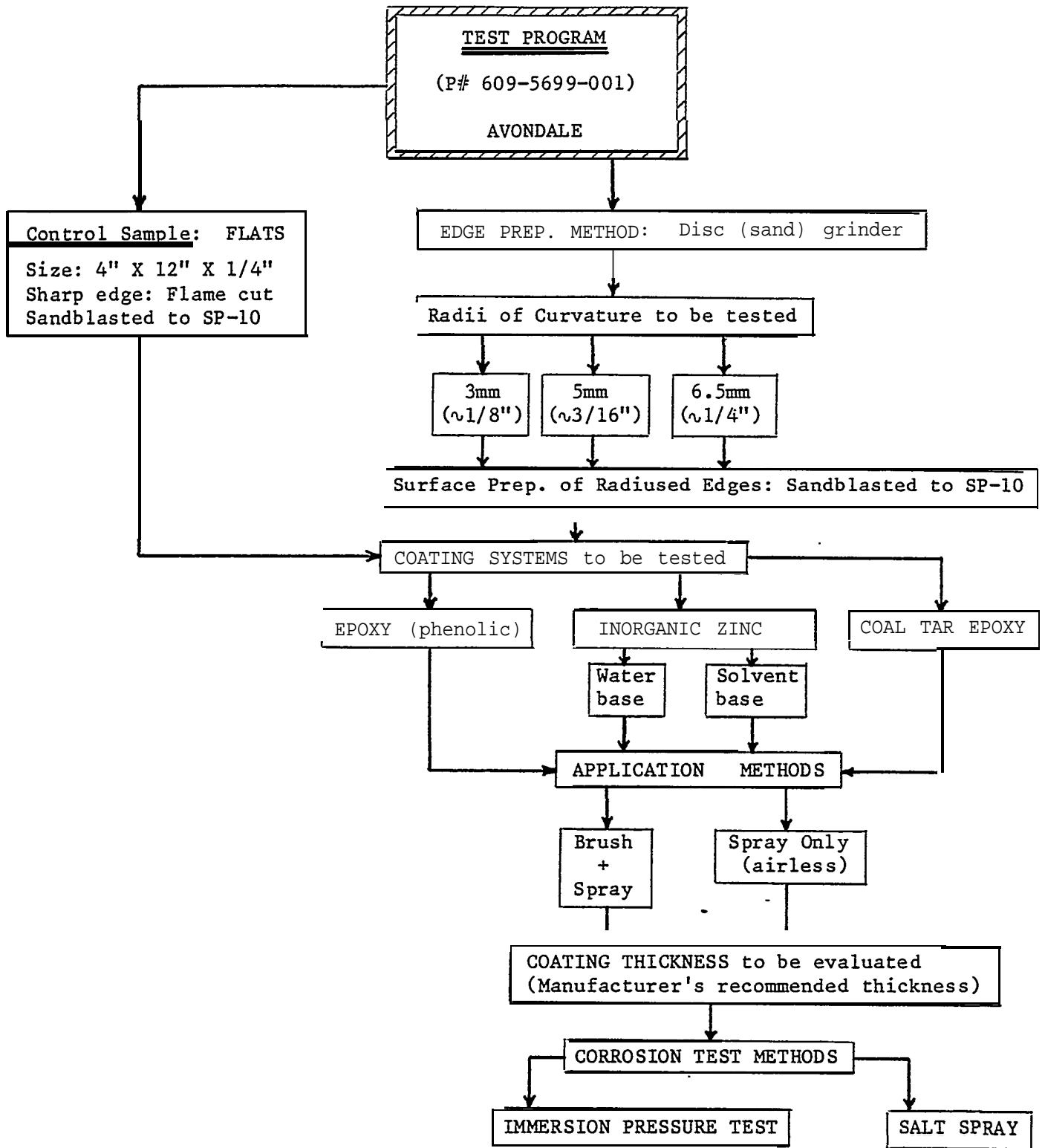
Types of coating failure found.

304 Zinc		5A Coal Tar		Polyamide Epoxy	
IPT	SST	IPT	SST	IPT	SST
Chipping	Chipping	Blistering	Blistering	No failure yet	Rusting
		Rusting	Rusting		
	Rusting	Chipping	Chipping		

TABLE II

Summary of final results.

Sample ID	304 Zinc		5A CO al Tar		Polyam ide Epoxy	
	IPT	SST	IPT	SST	IPT	SST
"F"	All failed	All failed	5 failed, 1 OK	All failed	All OK	2 failed, 4 OK
"4"	4 failed, 2 OK	5 failed, 1 OK	4 failed, 2 OK	All failed	All OK	All OK
"3"	4 failed, 2 OK	5 failed, 1 OK	All OK	4 failed, 2 OK	All OK	All OK
"2"	3 failed, 3 OK	All OK	All OK	All OK	All OK	All OK



OTHER TEST DETAILS:

- (1) Immersion test solution: 3% salt solution
 - ambient test temperature
 - cycling every 10 days (leave 2" on tank bottom)
 - test duration: 1st definite sign of rusting and/or blistering.
 - partial immersion to simulate tank conditions (vapor phase, interphase, immersed phase, tank bottom).
 - Test tank under lid for pressurization.
- (2) Three samples/edge radius. Total of 192 samples for test program.
- (3) Viscosity of each paint system to be determined.
- (4) Coating thickness on edges to be measured prior to testing.
- (5) Photographs to be taken to document
 - (5.1) surface condition of flats (control) and edges after sandblasting,
 - (5.2) condition of each coating system on edges and flats after curing per application method
 - (5.3) representative pictures after testing
- (6) CONCLUSIONS
- (7) RECOMMENDATIONS for REVIEW by SNAME PANEL #023-1.