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Project Summary

Reduced-Pollution Corrosion-Protection Systems

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This study evaluated newer less polluting metal plating materials and processes as potential alternatives to currently used plating systems. Viable replacements were established for cyanide cadmium, cyanide copper, and hexavalent chromium electroplating. Available alternatives to solvent-borne paints and phenolic-type paint strippers have slightly lower performance characteristics than their higher polluting counterparts. Through comprehensive testing performance characteristics were established for replacement systems of each type. The performance, economic, and environmental aspects of the new coating systems were compared to those for a control system currently in use.

Alternative coating systems evaluated for cyanide cadmium electroplating included non-cyanide cadmium electroplating, mechanical plating of cadmium and tin-cadmium, spray-and-bake aluminum-filled resin coatings, and ion-vapor-deposition (IVD) of aluminum. Each of these alternatives eliminated the cyanide waste treatment problem and the last two also eliminated the use of cadmium, another toxic material. Although none of the systems evaluated can be considered a better alternative to cyanide cadmium electroplating, each exhibited certain advantages while offering the same basic performance as cyanide cadmium plating. Non-cyanide copper electroplating (the alternative evaluated for cyanide copper electroplating) and trivalent chromium electroplating (the alternative to hexavalent chromium electroplating) were shown to provide performances comparable to their higher polluting, higher waste treatment requirement control systems.

Water-borne paints and power coatings, both of which eliminate the need for solvent collection systems in coating applications were evaluated as potential alternatives for solvent-borne paints. Although the performance characteristics of these water-borne paints and powder coatings were shown to be comparable to those for the solvent-borne control system, no single system provided equivalent performance for all characteristics.

Evaluation of non-phenolic paint strippers against phenolic strippers demonstrated the effectiveness of the non-phenolic strippers in eliminating the phenolic waste disposal problem. Both acid and non-acid immersion and brush-on type strippers were evaluated.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Mounting concern over environmental pollution, in light of more stringent EPA and OSHA regulations, has prompted the metal finishing industry to expand use of newer, less-polluting corrosion protection systems in place of currently used organic solvent systems and cyanide or cadmium plating solutions. The aerospace and metal finishing industries have available many new coating systems that can be considered as non-polluting or as having reduced-pollution characteristics compared to the currently used systems. Corrosion resistance data for these systems are limited, however, especially with respect to long-term exposure. As a result, customer confidence in these systems is not high and this has inhibited their widespread utilization. Understandably, the metal finishing industry is reluctant to the introduction of new systems for which supporting test data are limited and manufacturing costs are not clearly defined. The approach taken in this project was to evaluate and demonstrate the durability of these new systems by conducting extensive tests to meet the acceptance criteria of the aerospace and metal finishing industries.

Conclusions

Replacement Coatings for Cyanide-Cadmium Electroplating

Several replacement systems are available for cyanide-cadmium electroplating, including non-cyanide cadmium electroplating, mechanical plating, spray-and-bake aluminum coating, and ion-vapor-deposited (IVD) aluminum. These systems, each of which has advantages and disadvantages compared to conventional cadmium electroplating, can provide protection equivalent to that given by cyanide cadmium electroplating for various applications and cause fewer harmful environmental effects than cyanide cadmium electroplating. Kadizid*, a non-cyanide cadmium electroplating system, provides excellent adhesion and corrosion resistance with no sign of hydrogen embrittlement while eliminating the need for cyanide waste treatment. Transiflo*, a mechanically plated cadmium coating, provides good adhesion and excellent corrosion resistance with no sign of hydrogen embrittlement. No waste treatment is required for the Transiflo plating system. Alumazite Z*, a spray-and-bake aluminum coating, provides excellent adhesion and corrosion resistance with no sign of hydrogen embrittlement.Since no cyanides or cadmium is required with use of Alumazite Z, waste treatment problems are eliminated. Ivadize*, an ion-vapor-deposited (IVD) aluminum coating, provides excellent adhesion and corrosion resistance with no potential for hydrogen embrittlement. Again, no cyanide or cadmium is used in the process and, as before, waste treatment problems are eliminated.

Replacement Coatings for Organic Solvent-Borne Paints

Now available are water-borne paints and powder coatings that conform to the requirements of MIL-C-81773 (polyurethane topcoat). The hazards associated with the use of solvent-borne paints, as well as the need for solvent collection facilities, are eliminated with the use of either of these replacement coatings. Three of the water-borne paints evaluated, including one air-drying system and two bake-curing systems, have coating properties close to those for the control system. These include film properties (appearance, adhesion, impact, and flexibility), fluid resistance, and weatherability. Five of the powder coatings evaluated also have coating properties similar to those of the control system. These include film properties (appearance, adhesion, impact, and flexibility), fluid resistance, and weatherability.

Replacement Coatings for Cyanide Copper Electroplating

A non-cyanide copper electroplating system is available which is capable of performance equivalent to that of currently used cyanide-type copper electroplating systems per MIL-C-14550. Enthobrite Cu-942 provides excellent adhesion, solderability, and decarb protection with no sign of hydrogen embrittlement while eliminating the need for cyanide waste treatment.

Replacement Coatings for Hexavalent Chromium Plating

A trivalent chromium plating system, evaluated as a replacement for decorative hexavalent chromium electroplating, provided performance equivalent to that for the hexavalent system while eliminating the toxicity and waste treatment problems associated with hexavalent chromium. Trichrome showed good appearance, adhesion, and corrosion resistance, with no sign of hydrogen embrittlement.

Replacement Coatings for Phenolic Paint Strippers

Several acid and non-acid, brush-on and immersion-type, non-phenolic paint strippers show promise as potential replacements for phenolic paint strippers. The performance of these systems approximates that of the standard phenolic paint stripper (MIL-R-81294) in appearance, removal power, rinsability, coating and remover residue, and refinishability.

This technology development program established the availability of many new less-polluting corrosion protection systems as viable alternatives to present high-pollution systems. This effort has encouraged manufacturers to develop or improve less-polluting metal finishing systems. If the development efforts are continued, aerospace and metal finishing firms should be able to implement the following new systems with a high degree of confidence:

- Water-borne, chemical milling maskant systems evaluated under the present project. These systems show promise as replacements for high-polluting systems. Additional pilot-plant (50-gallon) testing on both typical flat and curved panels are needed to demonstrate the viability of these systems for future and most current commercial and military aircraft. This testing would provide the data needed to implement the less-polluting, water-borne maskants within the critical timeframe on such new aircraft as the 757 and 767 commercial airliners and ATF, FSW, V/STOL, AV-8B, and F-18 military aircraft.

- Improved water-borne paints, paint strippers, and spray-and-bake corrosion protection coatings are under development by several manufacturers. Development of these new products is seen to be a direct result of the favorable publicity that this program has received.

Evaluation of Results

Replacement Coatings for Cyanide-Cadmium Electroplating

Cadmium is normally plated from cyanide-type electroplating baths. The high level of toxicity of these baths necessitates the costly waste treatment procedures using either chlorine or hypochlorites be used to destroy the cyanide before disposing of these solutions. Several cyanide-free cadmium electroplating baths are now available; preliminary investigations indicate that these baths have potential as replacement systems. Mechanical plating of powdered cadmium also provides a potential alternative for cyanide-type cadmium electroplating.

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*Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S Environmental Protection Agency.

Table 1. *Cyanide Cadmium Replacement Coatings*

Cyanide Cadmium	Non-Cyanide Cadmium	Mechanical Plating	Spray-and-Bake Aluminum	IVD Aluminum
		Advantages		
● Readily available	● Reduces waste treatment req.	● Eliminates cyanides	● Eliminates cyanides	● Eliminates cyanides
● Techniques well-established	● Eliminates cyanides	● Eliminates hydrogen embrittlement	● Eliminates cadmium	● Eliminates cadmium
● Proven system	● Conversion costs low		● Reduces waste treatment req.	● Eliminates waste treatment req.
			● Eliminates hydrogen embrittlement	● Eliminates hydrogen embrittlement
			● Uses conventional spray equipment	● Use to 510°C (950°F) (CD limited to 232°C) (450°F)
			● Can be formulated for max performance	
		Disadvantages		
● Uses toxic chemicals	● Higher makeup cost	● Requires new equipment	● Organic solvent collection system req.	● Requires new equipment
● Requires costly waste treatment		● Part size limited		

Several aluminum coatings are also available as potential replacements for cadmium plating. Ion-vapor-deposited (IVD) aluminum and aluminum-filled resin spray-and-bake coatings are of particular interest because they would eliminate toxicity problems related to the use of cadmium.

Four types of potential replacement coatings (Table 1) for cyanide cadmium plating (non-cyanide cadmium, mechanical plating, spray-and-bake aluminum, and IVD aluminum) were tested to determine the best system available in each category and to aid in evaluating the relative merits of the four types. Three non-cyanide cadmium plating systems were evaluated as potential replacements for cadmium cyanide electroplating. These systems, Lea-Ronal's Kadizid, Lea-Ronal's Cad-Al, and Enthone's Enthobright CAD-935, were evaluated in Hull cell tests to determine throwing power and brightness. Cadmium and tin-cadmium applied by mechanical plating were also considered as potential replacement systems for cadmium cyanide electroplating. The 3M Company's Transiflo process was used to apply these coatings. Two spray-and-bake aluminum coatings were evaluated as potential replacements for cyanide cadmium plating. Alumazite Z from Tiodize and HiKote 3 from Hi Shear were applied to 4130 steel panels with and without MIL-P-23377 epoxy primer. The coatings were tested to determine their adhesion, corrosion, and fluid resistance. Panels of 4130 steel were coated with aluminum by McDonnell Douglas using their ion-vapor-deposition (IVD) process. A chromate conversion coating was applied to the coated panels.

The relative corrosion resistance of each coating system was determined using the 5%-salt spray corrosion test. Two to four panels of each system were subjected to 5%-salt spray until failure. Cyanide cadmium-plated panels were also run as controls. The corrosion resistance of a coating system, measured as time to failure, varies with the substrate to which it is applied.

Sustained load testing was conducted on selected coating systems to evaluate the potential for embrittlement failure resulting from hydrogen absorption. Notched tensile specimens made from both 300M and 4340 high-strength steels were coated with the various coating systems and subjected to a static load at 75% of the ultimate notched tensile strength for 200 hr or until failure. The ultimate notched tensile strength was determined by continuously loading uncoated specimens until failure.

The performance characteristics of each of the systems selected as replacements for cyanide cadmium plating approximated those of the cyanide cadmium control coating. Adhesion, corrosion resistance, and hydrogen embrittlement were evaluated for each of the selected coatings (Table 2). The adhesion of non-cyanide cadmium plate, spray-and-bake aluminum, and IVD aluminum was excellent. Satisfactory adhesion was obtained with the mechanical plating and cyanide cadmium control coatings. When considered against the minimum requirements of the QQ-P-416 and MIL-C-81562 specifications, corrosion resistance of the selected coatings is excellent. IVD aluminum showed excellent corrosion resistance on 4130 steel with minimal variation in results for the IVD aluminum. The Alumazite Z coating also showed slightly improved corrosion resistance over the cyanide cadmium plate for 4130 steel. No hydrogen embrittlement occurred as a result of coating application for any of the selected coatings.

Replacement Coatings for Organic Solvent-Borne Paints

Paints are used in many decorative and corrosion protection applications for home appliances, automobiles, aluminum siding, garden furniture, aircraft skins, and many other applications. Maskants are used to protect parts from being etched during the chemical milling process. Currently used paint and maskant systems employ organic solvents as volatile components. Toxicity of these organic solvents requires that stringent pollution-control procedures be followed in the use of these systems to meet established standards for maximum discharge levels. Besides increasing costs, additional problems associated with using organic solvent paints include flammability, rising prices, and decreasing availability of the solvents. The use of water as the solvent component virtually eliminates

Table 2. Cyanide Cadmium Replacement Coatings: Performance Summary

System	*Adhesion (bend test)*	*Corrosion resistance, hr to failure***			*Hydrogen embrittlement*
		4130	*4340*	*D6AC*	
*Cyanide cadmium electroplate**	*Good*	*576*	*2514*	*2172*	*Pass*
*Non-cyanide cadmium electroplate** *(Kadizid)*	*Excellent*	—	*2076*†	—	*Pass*
*Mechanical cadmium plating** *(Transiflo)*	*Good*	—	*2514*	*3522*	*Pass*
Spray-and-bake aluminum (Alumazite Z)	*Excellent*	*700*	—	—	*Pass*
*IVD aluminum** *(Ivadize)*	*Excellent*	*1752*	—	—	—

**Chromate conversion coating applied to plated panel.*

***Average of four panels.*

†*Average of two panels.*

these problems. Several of the water-borne paints currently available have been designed to withstand the applications mentioned above. Powder coatings, applied by fluidized bed or electrostatic powder spray, also eliminate the problems associated with organic solvents. Many different resins have been used for these 100%-solids resin systems, each with a different set of properties. Formulations of the same basic resin can be varied to adjust some of these properties. Several water-borne maskants have been developed to replace the organic solvent-type systems currently used for chemical milling applications.

Twelve water-borne paint systems, obtained from eight companies, were evaluated. Seven of these systems cure at room temperature; five require a higher temperature cure. Each of the systems, as well as the solvent-based control, were applied to aluminum panels that had been pretreated and alodined. Each topcoat was applied to the primer supplied for the system; in addition, several of the topcoats were applied to the solvent-based epoxy primer. The panels were then subjected to preliminary screening tests. These tests were performed in accordance with the requirements of MIL-P-23377 and MIL-C-81773. Of the properties tested, adhesion, impact, and flexibility were considered most important. Test results were analyzed to select the best coatings for further testing. Three of the coatings, Aquathane II and epoxy primer (air dry), Aqualure 634-W-804 with Aqualure primer (bake cure) and LP-3724 with LP-3779 primer (bake cure) provided the best combination of properties based on these criteria.

Eight powder coatings (acrylic, epoxy, polyamide, polyester [three types], nylon and vinyl) were evaluated. Each of these resins was applied by electrostatic powder spray to steel and aluminum panels. Nylon was also applied to aluminum and steel panels by a fluidized bed. A primer was used for the nylon and polyamide coatings. Coated panels were subjected to preliminary screening tests according to MIL-C-81773 procedures. As was the case with the water-borne paints, adhesion, impact, and flexibility were considered the most important of the properties tested. Some of the resins were applied at two coating thicknesses to evaluate the effect of thickness on coating properties.

Candidate water-borne maskants were subjected to preliminary screening tests to evaluate appearance, peelability, etchant resistance, line definition and scribability. Each of the maskants had a uniform appearance with no pin-holing or bubbling. The thickness of the Adcoat and Dee Aircraft maskants was 12 mils (0.0005 in.) while that of the Turco material was 8 mils (0.0003 in.).

Final characterization tests of the selected water-borne paints and powder coatings included additional fluid resistance tests, higher impact levels, and hydrolytic stability evaluation. The performance of the water-borne paints is comparable to that of the organic solvent paint control with respect to most properties; the bake-cure systems were slightly better than the air-dry systems. The selected powder coatings performed as well as or better than the organic-solvent paint control in most cases. The nylon powder coatings provided the best overall performance.

The selected water-borne paints and powder coatings applied to aluminum test panels were also subjected to 12 months of outdoor (southerly) exposure at Grumman's Test Site located in the U.S. Coast Guard Station at Fire Island, N.Y. The epoxy/polyurethane control system, as well as the Aquathane II and Aqualure 634-W-804 paint systems and the acrylic powder coating, resisted the 12-month weathering period rather well. The coated panels experienced no significant loss in properties. The epoxy powder coating on aluminum test panels also showed no significant loss in properties despite chalking and a severe loss of gloss; however, this coating on steel test panels had severe corrosion after 6 months' exposure. Although the oven-cured, water-borne paint system (LP 3778 primer and LP 3724 topcoat) showed no corrosion after 12 months' exposure, its adhesion, flexibility, and impact resistance decreased after 3 months' exposure. Polyester 156 coating applied to aluminum test panels experienced a slight decrease in impact resistance. When applied to steel test panels, however, the Polyester 156 coating showed evidence of corrosion around the panel edges after 3 months' exposure, with a slight decrease in flexibility and impact resistance. Both the nylon powder spray and fluidized-bed coating exhibited a sharp loss in gloss and a decrease in flexibility and impact resistance, even though no loss of adhesion occurred. The substrate used did not appear to affect the wearability of these coatings. The acrylic and polyamide powder spray coatings showed evidence of corrosion after 3 months' exposure and severe corrosion after 6 months' exposure, and were unable to undergo testing after 12 months' exposure (corrosion was too severe).

Replacement Coatings for Cyanide Copper Electroplating

Copper is normally plated from cyanide-type electroplating baths. The high level of toxicity of these baths necessitates the use of expensive waste treatment procedures involving either chlorine or hypochlorites to destroy the cyanides before disposing of these solutions. Several cyanide-free copper electroplating baths are available and have potential to become replacement systems. Five cyanide-free systems were evaluated and compared to the standard

Table 3. Non-Cyanide Copper Plating: Screening Tests

	Hull cell tests		*2.5 liter (0.66-gal) solution tests*						
System	*Bright range, A/m^2 (A/ft^2)*	*Throwing power*	*Current density, A/m^2 (A/ft^2)**	*Surface condition*	*Edges*	*Comments*	*Plating rate, μm/min (mil/min)*	*RMS value*	*Heat treat evaluation*
Mac Dermid Rocheltex (cyanide type control)	*11-387 (1-36)*	*Good*	*270 (25)*	*Smooth*	*Slight burning*	*Excessive gassing*	*0.495 (0.020)*	*55-100*	*Some decarb*
Lea-Ronal Cu-Pure	*11-324 (1-30)*	*Good*	*390 (36)*	*Smooth*	*Some burning*	*Some foaming*	*0.406 (0.016)*	*60-125*	*Minute decarb*
Enthone Cu-942	*11-1290 (1-120)*	*Excellent*	*780 (72)*	*Smooth and bright*	*No burning*	*No gassing or foaming*	*0.813 (0.032)*	*45-55*	*No decarb*
Harstan Fluoborate	*11-774 (1-72)*	*Poor*							
M&T AC-94	*11-324 (1-30)*	*Good*							
M&T Pyrophosphate	*11-234 (1-22)*	*Poor*							

**Optimum current density as determined by Hull cell tests.*

Mac Dermids' Rocheltex cyanide copper plating system. These include Cu-Pure and Unichrome Pyrophosphate (alkaline types), Enthobrite Cu-942 and AC-94 Bright Acid Copper (acid sulfate types), and Copper Fluoborate (acid fluoborate type). The five non-cyanide, copper plating systems were screened in Hull cell tests to determine bright range and throwing power (Table 3). Cu-Pure and Enthobrite Cu 942 were selected for final screening because they had the best combination of cost, maintenance requirements, and bright range/throwing power of the systems evaluated. Because the Enthobrite Cu-924 system did not gas or foam, gave a smooth bright plate with no edge burning, had a 60-100 percent higher plating rate, and provided better protection against steel decarburization, it was selected for further testing. Sustained-load tests were conducted to determine the extent of hydrogen absorption in acid copper-plated material and to evaluate the potential for embrittlement failure. All specimens exceeded the minimum test requirements without failure.

The characterization of Enthobrite Cu-942 showed that this non-cyanide copper plating system exceeded the requirements established for copper plating in MIL-C-14450 (Table 4). The adhesion and solderability of the copper plate were excellent. No hydrogen embrittlement was evident in notched tensile tests of the Cu-942-plated specimens. The Cu-942 plating adequately protected the steel from decarburization during heat treatment.

Table 4. Enthobrite Cu-942 Non-Cyanide Copper Plating Characterization Tests

Property	*Procedure*	*Results*
Thickness	*Permascope*	*28-33 μm @ 0.813 μm/min (1.1-1.3 mils @ 0.032 mils/min)*
Adhesion	*Sheet bend*	*Excellent**
Decarburization protection	*Metallographic examination*	*No decarburization*
Solderability	*Solder 232°C (450°F)-sheet bend*	*Excellent**
Hydrogen embrittlement	*75% UNTS/200 hr*	*Pass*

**Copper plate immediately following nickel strike.*

Replacement Coatings for Hexavalent Chromium Plating

Chromium is normally plated from hexavalent chromic acid electroplating baths for decorative application such as home appliances, marine hardware, automobile hardware, zinc die casting, brass forgings, and steel stampings. The toxicity and waste treatment requirements of hexavalent chromium compared to those of trivalent chromium make a trivalent chromium plating system desirable. Substrates to which chromium plating are commonly applied include 1010-1020 steel and 4340 high-strength steel. The pretreatment procedure includes vapor degreasing, alkaline cleaning, and reverse-etching of the metal surface to be plated. A nickel underplate is required for decorative chromium plating to provide good plate adhesion and maximum corrosion protection. The performance of trivalent chromium plating on buffed and unbuffed 1010 steel panels was screened with respect to appearance, corrosion-resistance and adhesion (Table 5). These tests showed that the appearance of both the trivalent and hexavalent chromium plate was excellent. Both types were smooth and bright, with the trivalent plate being somewhat brighter than the hexavalent plate. By comparison, the unbuffed panel plated with trivalent chromium was bright but not smooth, magnifying the orange-peel effect of the unbuffed panels. Plate adhesion was evaluated by bending the panels to break and examining the break at 4X magnification for lifting or peeling. No separation was evident at the

Table 5. Trivalent Chromium Plating: Evaluation of Properties

Property	*Trichrome* (unbuffed 1010 steel)*	*Trichrome* (buffed 1010 steel)*	*Hexavalent Chromium* (buffed 1010 steel)*
Appearance	*Bright*	*Smooth and very bright*	*Smooth and bright*
Adhesion (bend test)	*Poor*	*Good*	*Good*
Corrosion (salt spray)	*96 hr***	*282 hr****	*96 hr***

* *25.4 µm (1.0 mil) semi-bright nickel*
10.2 µm (0.4 mil) bright nickel
0.25 µm (0.01 mil) chrome (trivalent or hexavalent).

** *Each of 4 panels failed at 96 hr.*

*** *Average of 4 panels: 2 failed at 48 hr, 1 failed at 288 hr, 1 failed at 744 hr.*

chromium-nickel interface, the nickel-nickel interface, or the nickel-base metal interface on either the trivalent or hexavalent chromium plates on the buffed panels. The adhesion of the plate to the unbuffed panel, on the other hand, was poor (the underplate lifted from the substrate and the chromium separated from the underplate). This loss of adhesion was apparently due to the roughness of the substrate. Corrosion resistance was determined by exposure of four plated panels to 5%-salt spray solution until failure. Two trivalent chromium, buffed panels failed at 48 hr, one at 288 hr and one at 744 hr (an average of 282 hr). This average is considerably higher than that obtained with the hexavalent chromium panels, all four of which failed at 96 hr. Although the variation in the trivalent chromium results indicates that this bath may need further work to provide consistently higher corrosion protection, the results do show that trivalent chromium has excellent potential for providing improved corrosion protection over the hexavalent chromium while maintaining the performance in other properties.

In addition to the above tests hydrogen embrittlement tests were performed to provide final characterization of the chromium plating systems. Six notched tensile specimens of 4340 steel were heat treated to 1790-1930 MPa (260-280 ksi) and plated with duplex nickel and chromium. Three specimens were plated with trivalent chromium and three specimens were plated with hexavalent chromium. All specimens were baked for 3 hr at 191°C (375°F) following plating to provide embrittlement relief. Three bare control specimens were installed in a universal testing machine and continuously loaded until failure occurred to determine the ultimate notched tensile strength (UNTS). The average UNTS was found to be 56.5 MPa (389.3 ksi). The plated specimens were then subjected to a sustained load of 75% of the ultimate notched tensile strength for 200 hr. The trivalent chromium-plated specimens exceeded the 200-hr exposure with no failure. The hexavalent chromium-plated specimens all failed in less than 7 hr; however, since chromium plating on high-strength steel is normally baked for 23 hr to provide complete hydrogen embrittlement relief, hexavalent chromium-plated specimens should pass the notched tensile test. Differences in the nickel baths used for the trivalent and hexavalent chromium specimens may have contributed to these test failures.

Replacement Systems for Phenolic Paint Strippers

Paint strippers are widely used throughout the metal-finishing industry to remove paint from parts to permit repair, inspection, or refinishing. Most paint strippers contain chromates, methylene chloride, phenols, or strong acids. The normal procedure involves application of the paint stripper, allowing it to remain on the part for a specified time period and then washing it off with water. In many cases, the wash water containing the paint stripper and removed paint is fed into drains that go to leaching ponds or sewers. This can result in serious water pollution, especially when highly toxic chromates or phenols are involved. Several paint strippers containing no phenols have been developed as potential replacements for phenolic paint strippers.

The coating used for all paint stripper tests (MIL-P-23377 epoxy primer/MIL-C-81773 polyurethane topcoat systems) was applied to 2024-T3 aluminum alloy panels according to conventional procedures and air-dried for 7 days prior to use. The paint surface to be stripped was completely covered with remover, either by immersion or by brush. After the required contact time, the area was rinsed with water and the loosened paint removed by brushing.

Testing of potential replacement systems for phenolic paint strippers was performed to determine the best system available of each of the four types: acid brush-on, non-acid brush-on, acid immersion, and non-acid immersion. Strippers in each category were subjected to various screening tests applicable to that category and compared to the phenolic non-acid brush-on type stripper used as a control. Preliminary screening tests were conducted to determine the stripper's remover power, rinsability, coating and remover residue, and general properties.

Preliminary screening tests were conducted with the brush-on application strippers. The performance of the six candidate non-acid brush-on strippers varied widely; the removal power, or time required for completion of lifting, ranged from 20 to more than 80 min. This time was determined to be that required for completion of all lifting and wrinkling action, using a remover volume sufficient to completely cover the test area. A more quantitative removal power test, which determined the total area lifted in a specific time using a specific volume of remover, showed that two of the removers lifted the paint film in 30 min or less using a specific remover volume (Table 6). These removers, Sprazee (BASF Wyandotte Corp.) and T-5873 stripper (Turco Co.), also showed good rinsability, coating residue, and remover residue. Each of the three candidate acid brush-on strippers (Oakite Visstrip, Turco T-2822, and Turco T-6017) showed excellent removal power in both the time and area-lifted removal tests. These strippers also showed excellent rinsability, coating residue, and remover residue properties. The removers were then subjected to further evaluation. Sprazee and T-5873 strippers were selected from the non-acid brush-on strippers for further evaluation.

The refinishing properties of the selected brush-on strippers were determined by applying the paint system (epoxy primer per MIL-C-81773) to panels which had been stripped with each candidate system, and then testing to determine the adhesion, appearance, and gloss of the applied paint film. The

Table 6. *Brush-On Paint Strippers: Characterization Tests*

					Remover power						*Refinishing properties*		*Corrosion compatibility weight change, %***	
Manufacturer	*Trade name*	*Appearance*	*Consistency & How*	*Remover power, (time to lift, min:sec)*	*Contact time (min:sec)*	*Remover 10 ml (% lifted)*	*Volume 25 ml (% lifted)*	*Rinsability*	*Coating residue (% removed)*	*Remover residue*	*Gloss**	*Adhesion*	*Aluminum*	*Steel*
Phenolic control														
● *Turco*	*T-5469*	*Homogeneous*	*Smooth, even coat*	*5:17*	*5:30*	*100%*	*100%*	*Excellent*	*>99%*	*Much residue*	*91*	*Good*	*0.011%*	*+0.007%*
Non-phenolic non-acid														
● *BASF*	*Sprazee*	*Homogeneous*	*Fairly even coat*	*56:50*	*30:00*	*82%*	*97%*	*Good*	*96%*	*Easily rinsed*	*N.D.*	*N.D.****	*N.D.****	*N.D.****
● *Turco*	*T-5873*	*Homogeneous*	*Smooth, even coat*	*20:05*	*6:45*	*42%*	*100%*	*Excellent*	*>99%*	*Much residue*	*90*	*Good*	*+0.007%*	*+0.031%*
Non-phenolic, acid														
● *Oakite*	*Visstrip*	*Separated*	*Smooth, even coat*	*8:28*	*5:20*	*92%*	*97%*	*Excellent*	*95%*	*Easily rinsed*	*90*	*Good*	*Heavy corrosion*	*-0.055%*
● *Turco*	*T-2822*	*Homogeneous*	*Smooth, even coat*	*8:18*	*6:20*	*99%*	*99%*	*Excellent*	*>99%*	*Easily rinsed*	*91*	*Good*	*1.36%*	*-0.950%*
● *Turco*	*T-6017*	*Slight separation*	*Fairly even coat*	*3:20*	*3:10*	*87%*	*98%*	*Excellent*	*>99%*	*Easily rinsed*	*92*	*Some lifting*	*7.5%*	*+0.258%*

* *Gloss on original paint film: 94.*
***Maximum allowable weight change: aluminum ±0.016%; steel ±0.010%.*
*** *N.D. = Not determined.*

appearance of each of the refinished films was good, with a reduction in gloss from the original paint film of only 2 to 4 units. The adhesion of refinished films was determined by the wet tape test. Good adhesion was evident on all but one of the refinished films; in that one, which used the Turco T-6017 stripper, the topcoat lifted from the primer on one of the two panels; the other panel showed good adhesion. The corrosion compatibility of the selected paint strippers was also determined for aluminum and steel substrates. As expected, the acid paint strippers are not compatible with either aluminum or steel substrates. These substrates corroded to varying degrees after one week of exposure to the paint stripper at 38°C (100°F). The Turco T-5873 non-acid stripper also showed corrosion of the steel substrate.

The performance of the candidate immersion-type paint strippers was evaluated in tests similar to those used for the brush-on type removers; the major difference being the paint removal technique. Results are summarized in Table 7. One of the two non-acid immersion-type strippers evaluated (Magnus 766) showed good removal power and good rinsability, with 90% paint lifted after a 22-min contact time. Two acid-immersion paint strippers were evaluated; one of these (Oakite Stripper SA) showed good removal power with excellent rinsability and a coating residue of only 2% after an 11-min contact time. This stripper left a residue after contact with the bare substrate for 15-min at 38°C (100°F) and thorough rinsing. The refinishing properties and metal compatibility of the selected immersion paint strippers were also evaluated. The refinishing properties of both strippers were good, with a 5-unit loss of gloss compared to the original paint film and only slight lifting of the paint system and small blisters in the wet tape test of the Stripper SA-stripped panels. The corrosion tests show that the acid stripper was not compatible with either aluminum or steel, while the non-acid stripper (Magnus 766) was compatible only with the aluminum substrate.

Table 7. Immersion Paint Strippers: Preliminary Evaluation and Characterization

Manufacturer	Trade name	Appearance	Removal power (time to lift, min: sec)	Rinsability	Coating residue (% removed)	Remover residue	Refinishing properties		Corrosion compatibility weight change, %**	
							Gloss*	Adhesion	Aluminum	Steel
Non-phenolic, non-acid										
● BASF	Rapoff	Separated	>80.00	Good	<1%	Much residue	—	—	—	—
● Magnus	766	Slight separation	22:08	Good	90%	Some residue	89	Good	-0.003%	-0.112
Non-phenolic, acid										
● Oakite	Stripper EZ	Separated	>80:00	Fair	10%	Slight residue	—	—	—	—
● Oakite	Stripper SA	Homogeneous	11:08	Excellent	98%	Much residue	89	Sl lifting	-5.88%	-0.912

**Gloss on original paint film: 94.*

***Maximum allowable weight change. aluminum - ±0.016%; steel - ±0.010%.*

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The complete report, entitled "Reduced-Pollution Corrosion-Protection Systems," (Order No. PB 83-153 056; Cost: $13.00, subject to change) will be available only from:

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