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Ultra-High Pressure Water Jetting (UHP WJ)
:A Useful Tool for Deposit Removal and Surface Preparation

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ABSTRACT

This paper compares the following six different surface preparation methods: (1) abrasive blasting with mineral sands, (2) ultra-high pressure water jetting (UHP WJ) uninhibited, (3) UHP WJ inhibited, (4) UHP WJ with garnet, (5) UHP WJ with sodium bicarbonate, and (6) power tool cleaning with flapper wheel. Six different types of coupons were used for this test. Four different types of actual process equipment coupons and two different types of mill-scaled coupons were used.

The following laboratory tests were run on each type of coupon: (1) invisible surface contaminant detection using a boiling extraction method for sulfates, phosphates, chlorides and nitrates, (2) scanning electron microscope (SEM) of the surface before and after cleaning, (3) photomicrograph of edge profile,(4) surface profiles before and after the cleaning, and (5) weight loss. Comparisons between the abrasive blasted coupons and UHP WJ coupons were made for each type of coupon. Also, comparisons between abrasive blasting and power tool cleaning were made.

Keywords: ultra-high pressure, UHP, ultra-high pressure water jetting, UHP WJ, surface preparation, surface prep, water blasting, sandblasting, surface contaminants, invisible surface contaminants, soluble abrasives, abrasive blasting

INTRODUCTION

Abrasive blasting with sand has long been the surface preparation method of choice. It has been used primarily because (1) it is fast and economical, and (2) coating specialists want to see the surface profile. Consequently, most of the surface preparation specifications have been written on visual standards that have been derived from abrasive blasting with sand. However, problems with abrasive blasting have been discovered. For example, the health problems associated with abrasive blasting with sand include silicosis, which is caused by breathing silica from the sand. However, this problem can be eliminated by using blasting media other than sand. Another example includes the breathing of lead when abrasive blasting lead-based paints. The abrasive blasting industry has addressed the above problems by changing media types and using containment to isolate the environment and workers from these hazards.

Additional problems have been found with abrasive blasting. With the work done in the area of reducing invisible surface contaminants, abrasive blasting has again come under fire. It has been shown that abrasive blasting tends to trap contaminants in the crevices and foldovers created by the movement of surface metal., Also, it has been pointed out that creation of an additional surface profile on steel that already has a surface profile is not necessary.
Water blasting has long been used for removal of various deposits on such things as heat exchangers, towers, vessels, and other types of process equipment. Traditionally, conventional pressure hydrojetting, which is water blasting at pressures less than 10,000 psi (68,950 kPa), has been used. However, the Ultra-Jet™ System which uses a triplex pump and regulating valve capable of operating at 35,000 psi (241,325 kPa) is used for surface preparation work. (1) Figure 1 is a photograph of our UHP WJ system. This system can direct a rotating stream of water at velocities of 2,220 f/s (Mach 2) (677 m/s) at 35,000 psi (241,325 kPa) . The use of UHP WJ can take several forms. UHP WJ can be used for removal of process foulings, coating removal, and cutting through concrete or metal.

Many of the problems associated with abrasive blasting can be eliminated with UHP WJ. UHP WJ can be used effectively for recoating work that has been abrasive blasted previously. However, UHP WJ uninhibited, UHP WJ inhibited, and UHP WJ sodium bicarbonate do not create or change the surface profile on the steel. UHP WJ is a viable method for surface preparation and has been proven in field-testing for about 10 years. Our research has documented that UHP WJ is an excellent alternative to abrasive blasting in many applications.

Trademark of Halliburton Services for its UHP WJ System.

EXPERIMENTAL PROCEDURE

The following types of coupons were used for this testing:

- 1/4 in. thick (6.4 mm) A-36 [2] steel plate with mill scale intact with no coating.
- 1/4 in. thick (6.4 mm) A-285[2] Grade 3 steel plate with mill scale intact with no coating. Note: A-285[2] is a new specification for a material formally known as A-70[2]. The A-70[2] spec was abolished in 1927 . [2]
- 4 1/2 in. OD, 1/4 in. wall (11.43 cm OD, 6.4 mm wall) heavily rusted water service pipe. It had been in service for 10 years. The steel had been abrasive blasted to NACE No. 2 "Near-White Blast ,3 with a surface profile of 2 to 4 mils (51 µm to 102 /µm) . It is a coating system consisting of inorganic zinc primer, high build polyamide intermediate coat, and epoxy top coat.
- 4 1/2 in. OD, 7/16 in. wall (11.43 cm OD, 11.1 mm wall), intact coating on water service pipe. The coating specifications are unknown.
- H2S scrubber plate from sour water unit vessel with process fouling.
- 5/16 in. (7.9 mm) thick heat exchanger shell in propane service. Primer coat intact; however, most of top coat is gone.

All the above coupons were cut into 1 in. by 2 in. (2.54 cm by 5.08 cm) and 4 in. by 6 in. (10.16 cm by 15.24 cm) sizes for the laboratory testing.

The six different surface preparation methods used for this testing are as follows: (1) abrasive blasting with mineral sands, (2) UHP WJ uninhibited, (3) UHP WJ inhibited, (4) UHP WJ garnet, (5) UHP WJ sodium bicarbonate, and (6) power tool cleaning with f lapper wheel. All the coupons were cleaned to a "Near-White Blast" surface NACE No. 2 [3] with the exception of the power tool cleaned coupons which were cleaned to bare metal SSPC-SP 11-87T.[4] The more stringent bare metal specification was used because we felt it was unfair to compare the more stringent abrasive-blasted specification to the less stringent power tool-cleaned SSPC-SP 3. [4]

It should be pointed out that the UHP WJ surf aces did not have the shiny appearance that a near-white abrasive blasted surf ace does. Sometimes people in the coatings industry claim that a surface does not meet a particular specification because it is a dark grey color and looks slightly different. NACE 5 and SSpC6 are addressing this issue by working on a water jetting visual comparator and specification.

All the UHP WJ cleaning was done by using a pump operating at 35,000 psi (241,325 kPa). Figure 2 is a photograph of coupons being blasted using UHP WJ uninhibited. UHP WJ uninhibited was run using only city water. The UHP WJ uninhibited cleaned coupons experienced flash rusting in 3 to 5 minutes after cleaning. This flash rusting was a very thin and uniform gold tint; however, no localized corrosion appeared on the steel surfaces. Frenzel has pointed out that flash rusting should not be a problem for good coatings.' For recoating work in the field, a flash rust inhibitor is usually used so that rusting does not occur on the equipment. The cleaning methods UHP WJ inhibited and UHP WJ garnet used a short-term flash rust inhibitor injected into the pump suction at a ratio of 1 to 300. The cleaning method UHP WJ with sodiumbicarbonate used a short term flash rust inhibitor that was applied manually with a sprayer after blasting was complete.

Each type of coupon was cleaned by each of the six surf ace preparation methods. Comparisons between the abrasive blasted coupons and the UHP WJ coupons were made for each type of coupon. Also, comparisons between abrasive blasting and power tool cleaning were made. Most of the comparisons were made to abrasive blasting because it is the most popular surface preparation method. No specific attempt was made to determine which of the UHP WJ methods performed best.

Work has been conducted in the area of evaluating the cleanliness of steel coupons that have been cleaned by UHP WJ. This previous work has focused on traditional cleaning specifications such as visual cleanliness, surface profile, photomicrographs of edge profile, and weight loss.[1,7] Also, the concept of invisible surface contaminant detection was used in the paper presented by Frenzel. [1,7] For example, Frenzel uses a scanning electron microscope (SEM) equipped with energy dispersive X-ray analysis (EDAX) to look for such things as ferrous salts, silica, chlorine, phosphorus and sulfur. [1] Also, Frenzel uses Fourier Transform Infrared Spectroscopy (FTIR) and Raman Spectroscopy to look at such things as phosphate and nitrate. [1] On the other hand, there are industry researchers looking at only surface contaminants who approach the detection of surface contaminants from a different direction.

A lot of work has been done in the area of detection of surface contaminants and the development of laboratory and field techniques to measure them. Without a doubt, the method of choice for the surface contaminant community is the boiling extraction method. For example, Boocock has presented a paper to the Steel Structures Painting Council (SSPC)[6] titled "Detection and Significance of Surface Contaminants,"[8] and he has this to say about a boiling extraction method: "This is considered to be the most rigorous practical means for extracting the greatest amount of soluble salt. "[8] In our testing, we combined the work done by Frenzel, [7] and complemented it by using a boiling extraction method for determining invisible surface contaminants. [8]

The coating industry has long been determining what is considered "clean" so that the coating will enjoy a long life. Early belief was that using visual comparisons would be a good measurement of the cleanliness of a steel surface. Also, the measurement of the surface profile is used to determine if the coating system will have good adhesion. The importance of the visual cleanliness and surface profile has been questioned, and it is thought that they may not be good methods to determine how long a coating will last. However, it is still important to measure these parameters because they are important to coating specialists. Today, many in the surface preparation industry are looking at the surface contaminant cleanliness to foresee coating failures. We felt it was important to use the invisible surface contaminants and the traditional surface preparation standards. On each type of coupon, we ran the following laboratory tests to evaluate the cleanliness of the steel.

Experimental Procedure For Invisible Surface Contaminants

The surface contaminant portion of our testing was used to look for sulfates, phosphates, chlorides, and nitrates. Chlorides and sulfates seem to be the most important contaminants. For our testing, we used the criterion established by Appleman in his article titled, "Painting Over Soluble Salts: A Perspective", for determining the safe levels of contaminants.[9] Appleman found that levels of chlorides of 7 $\mu g/cm^2$ and sulfate levels of 16 $\mu g/cm^2$ can cause blistering on thin films.[9]

For this testing, all our surface contaminant tests were considered safe if the levels of chlorides were less than 7 $\mu g/cm^2$ and sulfate levels were less than 16 $\mu g/cm^2$. .[9] The levels of phosphates and nitrates were determined because an inhibitor was used during much of the testing. The inhibitor used in the testing contains phosphates and nitrites. The levels of phosphates and nitrates were recorded on all of the coupons. However, no attempt was made to ' determine the safe levels of phosphates and nitrates. These results should be used only as representative levels remaining on surfaces. We could not find any published information on safe levels of phosphates and nitrates on steel surfaces. The only comparisons we made on phosphates and nitrates were made when the levels appeared out of the ordinary.

Inhibitors have been used in the wet blast industry with no adverse affect on coatings. one should consult with the various flash rust inhibitor manufacturers for effects of inhibitors on various types of coatings.

A modified version of a SSPC [6] boiling extraction method was used for our testing. The boiling extraction method we used involved placing the coupons in boiling distilled water for 30 minutes. [10] The water was allowed to cool and the volume was diluted to 100 milliliters. [10] A blank was run to correct for any contamination from glassware or testing procedures. The following American Society For Testing and Materials (ASTM)[2] methods were used in our testing: (1) Sulfates ASTM2 D 516, (2) Phosphates ASTM2 D 515, (3) Nitrates ASTM2 D 3867, and (4) Chlorides ASTM2 D 512. All results from the boiling extraction were given in $\mu g/cm^2$. Figure 3 is a photograph of boiling extraction analysis for phosphates. Special care was taken to eliminate any contamination of the samples used in the boiling extraction testing. The boiling extraction samples were handled by tongs that had been boiled for 30 minutes in distilled water. The samples were then transported to the laboratory and work was begun immediately on extracting the surface contaminants.

Experimental Procedure For Scanning Electron Microscope (SEM)

The SEM equipped with EDAX was used to look for chlorine, sulfur, and phosphorus and to take photos of the edge profile. SEM elemental analysis and photomicrographs of edge profile are being taken in Fig. 4. We assume that the chlorine found by the SEM with EDAX is actually chlorides. The surf ace was viewed before and after the cleaning. A total of 43 coupons were analyzed for this portion of our testing. Unfortunately, we were able to find chlorine only once while using the EDAX. We believe that the concentration level of chlorides on the coupons was so small that the SEM could not detect it. However, the SEM may be effective on samples that are heavily salted such as bridge samples. The boiling extraction method showed chlorides on most samples, but we detected chlorides only once using the SEM equipped with EDAX. However, the SEM with EDAX did give us levels of phosphorus, silicon, and iron. Also, the SEM gave excellent photomicrographs of the edge profile.

Experimental Procedure For Photomicrographs of the Edge Profile

The purpose of this testing was to detect any distortion that may have been created by all the cleaning methods. It is the photomicrographs of the edge profile that allow us to view the crevices where contaminants could become trapped. Each type of coupon had photomicrographs made before and after the cleaning. Photomicrographs of the edge profile are being taken in Fig. 4. This allowed us to compare the amount of rust on the coupon before it was cleaned and after the surface was cleaned. Small pieces of the coupons were mounted in epoxy so that the edge profile could be viewed. Each sample was then ground past the metal distorted by cutting the coupon. Next, the coupon was polished. The samples then were taken to the SEM so that elemental analysis and photomicrographs of the edge profile could be taken.

Experimental Procedure For Surface Profile

Surface profile is an important parameter when evaluating surface cleanliness. It is widely accepted that the use of UHP WJ uninhibited, UHP WJ inhibited, and UHP WJ sodium bicarbonate should only be used on equipment that already has a surface profile, i.e., equipment that has been abrasive blasted once. UHP WJ uninhibited, UHP WJ inhibited, and UHP WJ sodium bicarbonate do not remove mill scale at an economical rate and do not create a surface profile. The surface profile was measured before and after each coupon type was cleaned. The surface profile measurements were taken by ASTM [2] D 4417.

Experimental Procedure For Weight Loss

Weight loss of each coupon type was taken for every cleaning method. The purpose of this was to determine how much rust scale was removed from the surface and to determine if any of the cleaning methods tended to remove more rust and base metal. Each of the weight loss coupons were 1 in. by 2 in. (2.54 cm by 5.08 cm) and weighed in the 65 g range.

RESULTS FROM SURFACE CONTAMINANT TESTING

The results for the surface contaminants portion of the testing is shown in Tables 1 through 6. Surface contaminant levels in tables 1 through 6 were obtained by averaging the results from three coupons. Remember, the following guidelines were considered safe in our testing: sulfates less than 16 $\mu g/cm^2$, and chloride levels less than 7 $\mu g/cm^2$.[9] It should be pointed out that coatings can fail at levels below the guidelines used for this testing. Also, coatings can withstand surface contaminants at levels above those used as the guidelines of our testing. A coating specialist should be consulted on what levels of surface contaminants can cause failures for a particular coating system.

Results From Surface Contaminant Testing For A-36[2] Mill-Scaled Steel

Table 1 contains the results from surface contaminant testing for the A-36[2] mill-scaled steel. The uncleaned coupons contained safe levels of chlorides. However, the uncleaned coupons did have unsafe levels of sulfates which were 40 $\mu g/cm^2$. The abrasive blasted coupons did remove sulfates and chlorides to safe levels for the A-36[2] coupons. The UHP WJ uninhibited removed sulfates and chlorides to safe levels. Note that the UHP WJ uninhibited overall had the smallest amount of surface contaminants on the surface. The UHP WJ inhibited, UHP WJ garnet, and flapper wheel removed sulfates and chlorides to safe levels. The UHP WJ sodium bicarbonate removed the sulfates and chlorides to safe levels. **NOTE:** The phosphate and nitrate levels are much higher on the UHP WJ sodium bicarbonate coupons than the UHP WJ inhibited and UHP WJ garnet coupons. Tests determined that the sodium bicarbonate was not the source of the higher levels of phosphates and nitrates. The two most popular methods of injecting the inhibitor are (1) injecting in the pump suction, and (2) manually spraying the inhibitor on the surface. For this testing, both methods were used to determine if there were any differences. The UHP WJ sodium bicarbonate had the inhibitor added by manually spraying the surface after the blasting was complete. We believe this is the reason for higher levels of phosphates and nitrates. Normally we do not spray inhibitor on the surface after cleaning is complete. We inject the inhibitor at the pump suction as was done on the UHP WJ inhibited and UHP WJ garnet, both of which showed much lower levels of phosphates and nitrates.

Results from Surface Contaminant Testing for A-285[2] Grade 3 Mill Scaled Steel

The results from the surface contaminant testing for the A-285[2] mill-scaled steel are shown in Table 2. Uncleaned coupons did not contain unsafe levels of sulfates or chlorides. The abrasive-blasted, UHP WJ uninhibited, UHP WJ inhibited, UHP WJ garnet, and flapper wheel removed the sulfates and chlorides to safe levels. Also, UHP WJ sodium bicarbonate did remove the sulfates and chlorides to safe levels. Again, the UHP WJ sodium bicarbonate had higher levels of phosphates and nitrates than UHP WJ inhibited and UHP WJ garnet. For the reasons listed earlier, it is believed that this is a result of applying the inhibitor with a spray bottle.

Results from Surface Contaminant Testing For Heavily Rusted Water service Pipe

Table 3 contains the results from the surface contaminant testing for the heavily rusted water service pipe. The uncleaned coupons did have safe levels of sulfates. However, chloride levels were unsafe at 28 pg/cm~. Abrasive blasting removed the sulfates to safe levels but did not produce safe levels of chlorides at 32 11g/CM2. UHP WJ uninhibited, UHP WJ inhibited, UHP WJ garnet, UHP WJ sodium bicarbonate, and flapper wheel removed sulfates and chlorides to safe levels. The UHP WJ sodium bicarbonate produced higher levels of phosphates and nitrates than UHP WJ inhibited and UHP WJ garnet.

Results From Surface Contaminant Testing for Intact Coating on water Service Pipe

The results from the surface contaminant testing for the intact coating on water service pipe are shown in Table 4. The uncleaned coupons did have safe levels of sulfates and chlorides. Abrasive blasted, UHP WJ uninhibited, UHP WJ garnet, and flapper wheel did have safe levels of sulfates and chlorides. Also, the UHP WJ inhibited coupons contained safe levels of sulfates and chlorides. The UHP WJ sodium bicarbonate had safe levels of sulfates and chlorides. As for the case where all the coupons were sprayed with inhibitor, the UHP WJ sodium bicarbonate did have higher levels of phosphates and nitrates than UHP WJ inhibited and UHP WJ garnet.

Results From Surface Contaminant Testing For H2S Scrubber Plate From Sour Water Unit With Process Fouling

Table 5 contains the results from the surface contaminant testing for the H2S scrubber plate from a sour water unit with process fouling. The uncleaned coupons did have unsafe levels of sulfates at 39 $\mu g/cm^2$ and chlorides at 12 $\mu g/cm^2$. Abrasive blasting did remove the sulfates to safe levels, but abrasive blasting did produce unsafe levels of chlorides at 8 $\mu g/cm^2$. UHP WJ uninhibited, UHP WJ garnet, and flapper wheel did remove sulfates and chlorides to safe levels, and UHP WJ inhibited did remove chlorides to safe levels; however, the sulfates were at unsafe levels of 44 $\mu g/cm^2$. NOTE: The inhibitor used for the UHP WJ inhibited was determined to be defective by the manufacturer. It is possible that the defective inhibitor could have been the culprit for this high sulfate number. It should be noted that a good inhibitor was used on UHP WJ garnet and did not exhibit any high sulfates. Future work will include rerunning the boiling extraction testing for the UHP WJ inhibited coupons. This testing will determine if our speculations on the defective inhibitor are correct.

Of all the UHP WJ cleaning methods, the sulfate levels were unsafe in only two out of 24 instances. Both of these times occurred when using the defective inhibitor. All the other UHP WJ methods used did produce safe levels of sulfates. UHP WJ sodium bicarbonate did remove sulfates to safe levels, but UHP WJ sodium bicarbonate did produce unsafe levels of chlorides at 11 $\mu g/cm^2$. The high levels of phosphate and nitrates can be traced to applying the inhibitor with a spray bottle; however, the unsafe chloride number for UHP WJ sodium bicarbonate probably resulted from a localized corrosion site that was not completely cleaned.

Results From Surface Contaminant Testing For Heat Exchanger Shell in Propane surface

The results from surface ***contaminant testing*** for a heat exchanger shell in propane surface are shown in Table 6. Uncleaned coupons had safe levels of sulfates; however, the uncleaned coupon had unsafe levels of chlorides at 17 $\mu g/cm^2$. Abrasive-blasted coupons had safe levels of sulfates; however, the abrasive blasted coupons had unsafe levels of chlorides at 31 $\mu g/cm^2$. UHP WJ uninhibited, UHP WJ garnet, and flapper wheel coupons showed sulfates and chlorides at safe levels. UHP WJ inhibited did remove chlorides to safe levels, but UHP WJ inhibited did not remove sulfates to safe levels at 24 $\mu g/cm^2$ (SEE NOTE ABOVE)**.** Again, it should be noted that the defective inhibitor was used for the UHP WJ inhibited. The UHP WJ sodium bicarbonate did remove sulfates and chlorides to safe levels. As in other cases where inhibitor was added by manually spraying the surface, UHP WJ sodium bicarbonate again showed higher levels of phosphates at 39 $\mu g/cm^2$ and nitrates at 204 $\mu g/cm^2$.

Results Of Residue Analysis From Boiling Extraction Coupons

By the end of the boiling extraction portion of our testing, an interesting trend developed in the sample bottles containing the extracted water. A residue developed in the sample bottles of extracted water. This residue was solids that were remaining on the coupons after they had been cleaned. Analysis of this residue determined it to be about 80% rust.

Figure 5 shows the extracted water taken from the heat exchanger shell in propane service coupons. Sample 573 is from an abrasive-blasted coupon, Sample 572 is from a UHP WJ uninhibited coupon, Sample 553 is from a UHP WJ inhibited coupon, Sample 529 is from a UHP WJ garnet coupon, Sample 512 is from a UHP WJ sodium bicarbonate coupon, and Sample 503 is from a flapper wheel coupon. This photo is representative of all the coupon types used in the testing.

Table 7 contains the results of residue analysis from boiling extraction coupons. Table 7 was generated by measuring the residue contained in each sample bottle shown in Figure 5. Figure 5 does not show the extracted water from an uncleaned coupon; however, the uncleaned Sample 534 had a residue level of 121 $\mu g/cm^2$. The abrasive blasted coupon had a 50 $\mu g/cm^2$ layer of residue remaining on the coupon. The residue was probably contained in the crevices and hidden by the distortions of the metal. The UHP WJ uninhibited coupon had a residue layer of 39 $\mu g/cm^2$; residue is probably from the flash rusting that occurs when using UHP WJ uninhibited. A residue level of 27 $\mu g/cm^2$ was measured for the UHP WJ inhibited coupon. Note how the level of residue is reduced by using the flash rust inhibitor. The UHP WJ Garnet coupon had a residue concentration of 17 $\mu g/cm^2$. The lowest residue level of 8 $\mu g/cm^2$ was measured for the UHP WJ sodium bicarbonate coupon. Since the flapper wheel coupon was ground to bare metal, very little rust appeared in the extracted water. A residue level 27 $\mu g/cm^2$ was measured for the flapper wheel coupon.

Results of the Residue Analysis From the Boiling Extraction Coupons show the benefit of using the various UHP WJ techniques. All of the UHP WJ techniques do indeed leave the steel with significantly less residue than abrasive blasting. The UHP WJ is able to remove rust from the crevices and distortions in the metal surface. Also, power tool cleaning to bare metal does reduce residue levels to that of the UHP WJ inhibited.

SCANNING ELECTRON MICROSCOPE (SEM) RESULTS BEFORE AND AFTER CLEANING

The results of SEM work did not show any significant levels of sulfur or chlorine. our experience with the SEM was that the levels of contaminants were too small to be detected. Of the 43 coupons studied, only two coupons were found with chlorine or sulfur. An A-285 [2] mill-scaled coupon before cleaning contained sulfur at levels of 1.6%. The uncleaned samples such as Sample 101B did show sulfates in the boiling extraction. A heat exchanger shell type coupon which had been cleaned by a flapper wheel contained aluminum at 1.7%, iron at 98.11%, silicon at 0.75%, and chlorine at 0.97%. It should be noted that the boiling extraction method showed chlorides and sulfates on many samples; however, the SEM detected contaminants on only two coupons. Also, we looked at larger surface areas other than the edge profiles and still did not detect chlorides.

FTIR RESULTS BEFORE AND AFTER CLEANING

For our testing, we also tried using the FTIR to look for sulfates, phosphates, and nitrates. This testing was conducted during one-third of our testing and then discontinued because no results were recorded. The boiling extraction method detected sulfates, phosphates, and nitrates on most coupons; however, the FTIR was unable to detect sulfates, phosphates, and nitrates even on the original uncleaned coupons. We detected phosphates on the UHP WJ inhibited coupons using the FTIR. This is obvious because the inhibitor is a nitrite phosphate-type inhibitor. We feel the concentrations of sulfates, phosphates, and nitrates on our coupons were too low to be detected by the FTIR. It should be noted that the FTIR did detect silica and epoxy coating remaining on abrasive blasted coupons. However, nothing of interest was detected on the UHP WJ uninhibited coupons.

PHOTOMICROGRAPHS OF EDGE PROFILE RESULTS

Before looking at the photomicrographs, Figures 6 through 8 are before and after photos of three cleaning methods used on the intact coating on water service pipe coupons. Figure 6 was taken after the coupon had been cleaned by abrasive blasting. Figure 7 shows the intact coating on water service pipe cleaned by UHP WJ inhibited. Figure 8 shows the intact coating on water service pipe cleaned by a flapper wheel. Note the metal distortion created by the flapper wheel in Fig. 8.

The SEM was used to provide some high quality photomicrographs of the edge profile. Figures 9 through 16 show the intact coating on water service pipe coupons. Figure 9 is a before-cleaning photomicrograph of Sample W338B which shows the base metal in white; heavy rust layer above in gray; a scale layer consisting of iron, aluminum, and silicon; and epoxy shown in black. Figure 10 is another before-cleaning photomicrograph of Sample W338B. Since the coating was intact, it is a more representative photo of the surface before cleaning. Figure 11 shows Sample W338 cleaned by abrasive blasting; the sample is very clean with minimum rust remaining. Note the fuzzy surface created by the abrasive blasting. Figure 12 is of Sample 332 cleaned by UHP WJ uninhibited; the sample is very clean with little rust remaining. The gray area on the right-hand side is a small piece of rust. This is a result of flash rusting. Note how the surface of the metal is much smoother than the abrasive-blasted coupon. Figure 13 shows Sample 315 cleaned by UHP WJ inhibited which has a very smooth and clean edge. Note how the UHP WJ inhibited was able to clean out the crevice in the center of the photomicrograph. Figure 14 shows Sample 324 cleaned by UHP WJ garnet; the sample shows no scale present on the metal surface. Figure 15 is of Sample 323 cleaned by UHP WJ sodium bicarbonate; the sample is very clean with no rust remaining. As with other UHP WJ methods, the surface is much smoother than the abrasive-blasted. Figure 16 is of Sample 374 cleaned using a flapper wheel; the sample is clean with no rust. Note how the surface profile has been greatly reduced by grinding.

An interesting trend developed on all the abrasive-blasted coupons: The abrasive-blasted coupons had a fuzzy interface between the epoxy and base metal. This fuzzy interface was indistinct and undefined. It was created by the distortion of the metal that occurs while abrasive-blasting.

A-36 [2] Mill-Scaled Steel Photomicrograph Results

Figure 17 is of the A-36 [2] mill-scaled steel cleaned by abrasive blasting which shows the mill scale removed. Figure 18 is of the A-36[2] mill-scaled steel cleaned by UHP WJ uninhibited; the sample shows a much smoother and distinct interface between the epoxy and base metal. Figure 19 is of the A-36 [2] mill-scaled steel cleaned by UHP WJ inhibited; the sample shows the smooth distinct interface between epoxy and base metal. Note the crack in this sample; gray areas are rust and black areas are epoxy. The UHP WJ inhibited actually cleaned down in the crack until the black area became gray.

A-2 85[2] Mill-Scaled Steel Photomicrograph Results

Figure 20 is of the A-285[2] mill-scaled steel cleaned by abrasive blasting; the sample shows no rust layer. Again, there is a fuzzy interface between the epoxy and base metal. Figure 21 is of the A-285[2] mill-scaled steel cleaned by UHP WJ uninhibited; the sample shows the smooth distinct interface between epoxy and base metal. Figure 22 is of the A-285[2] mill-scaled steel cleaned by UHP WJ inhibited; the sample shows a distinct interface.

Heavily Rusted Water Service Pipe Photomicrograph Results

Figure 23 is of the heavily rusted water service pipe cleaned by abrasive blasting. As in the case with the other abrasive-blasted coupons, the interface is fuzzy. It should be noted that a light layer of rust was remaining on this coupon. Figure 24 is of the heavily rusted water service pipe cleaned by UHP WJ uninhibited; the sample shows a smooth interface between epoxy and base metal. Another smooth interface between epoxy and base metal is shown in Fig. 25 for the heavily rusted pipe which is cleaned by UHP WJ inhibited.

H_2S Scrubber Plate From sour water unit with Process Fouling Photomicrograph Results

Figure 26 is for the H_2S scrubber plate cleaned by abrasive blasting which shows the fuzzy interface between the epoxy and base metal. Figure 27 shows the H_2S scrubber plate which contains a smooth interface created by cleaning with UHP WJ uninhibited. Figure 28 is of H_2S scrubber plate cleaned by UHP WJ inhibited which creates a smooth interface. Note how the UHP WJ uninhibited and inhibited removes rust all the way to base metal and leaves the crevices very clean.

Heat Exchanger Shell in Propane Service Photomicrograph Results

Figure 29 is of the heat exchanger shell cleaned by abrasive blasting which shows the irregular interface between the epoxy and base metal. Figure 30 is of the heat exchanger shell cleaned by UHP WJ uninhibited which shows a distinct interface. Figure 31 is of the heat exchanger shell cleaned by UHP WJ inhibited. Note the distinct interface. Again, all the rust to base metal and crevices are very clean by cleaning with UHP WJ uninhibited and inhibited.

SURFACE PROFILE RESULTS BEFORE AND AFTER CLEANING

The surface profile results are shown in Tables 8 through 13. The before-cleaning results were taken with mill-scale and coatings intact. The after-cleaning results represent the surface profile after the surface was cleaned.

Surface Profile Results For A-36[2] Mill-Scaled Steel

Table 8 shows the surface profile results for A-36[2] mill-scaled coupons. The before-cleaning results were taken with mill scale intact. As expected, the abrasive-blasted coupons showed a change in surface profile. UHP WJ uninhibited, UHP WJ inhibited, and UHP WJ sodium bicarbonate coupons did not show any significant change in surface profile. However, UHP WJ garnet coupons did show a slight change in surface profile from 2.6 mils (66 μm) before to 2.2 mils (56 μm) after. It should be noted that the surface of the UHP WJ garnet coupons looked similar to that of an abrasive-blasted surface. It had a white appearance with uniform roughness. The flapper wheel coupons showed the most dramatic change in surface profile. The surface profile was 2.5 mils (64 µm) before and 1.3 mils (33 µm) after cleaning with a flapper wheel.

Surface Profile Results For A-285 [2] Grade 3 Mill-Scaled Steel

Table 9 shows the surface profile results for A-285[2] Mill_ scaled coupons. The before-cleaning results were taken with mill scale intact. As with the A-36[2] , the abrasive blasted coupons showed a change in surface profile. UHP WJ uninhibited and UHP WJ inhibited coupons did not show any significant change in surface profile. UHP WJ sodium bicarbonate coupons showed a minor change in surface profile; however, it was not a uniform profile, and most inspectors would not consider this change to be significant and would not be impressed with the surf ace. Also, the UHP WJ sodium bicarbonate had a whiter color than the UHP WJ uninhibited and inhibited coupons, but the color was not uniform, and the surface area contained a large percentage of discolorations. The UHP WJ garnet coupons had a surface profile of 2.4 mils (61 µm) before and 2.1 mils (53 µm) after. Again, the surface resembled an abrasive-blasted surface. The flapper wheel-cleaned coupons had a dramatic change in surface profile from 2.5 mils (64 µm) before to 1.2 mils (30 µm) after.

Surface Profile Results For Heavily Rusted Water Service Pipe

The surface profile results are shown in Table 10 for the heavily rusted water service pipe. Overall, the surface profile before and after cleaning varied significantly on most of the cleaning methods. Undoubtedly, this was caused by the heavy rust buildup. The profile of the abrasive-blasted coupons was reduced from 5.1 mils (130 µm) before to 3.8 mils (97 µm) after cleaning. The UHP WJ uninhibited coupons experienced a change from 4.0 mils (102 µm) before to 3.6 mils (91 µm) after cleaning. The surface profile showed almost no change in the UHP WJ inhibited coupons. The surface profile changed from 4.1 mils (104 µm) before to 3.2 mils (81 µm) after cleaning by UHP WJ garnet. Again, the surface looked very similar to an abrasive-blasted surface; the only visual difference was less depth of the surface profile and the surface was a lighter gray color. The UHP WJ sodium bicarbonate showed a change from 4.0 mils (102 µm) before to 2.7 mils (69 µm) after cleaning. As with all the previous cases, the flapper wheel-cleaned coupons experienced the largest change in surface profile.

Surface Profile Results For Intact Coating On Water Service Pipe

The surface profile results are shown in Table 11 for the intact coating on water service pipe coupons. The abrasive-blasted coupons had almost no change in surface profile. The UHP WJ uninhibited, UHP WJ inhibited, and UHP WJ garnet coupons all showed changes of about 1 mil (25 µm). The UHP WJ sodium bicarbonate coupons exhibited no change in surface profile. The flapper wheel coupons experienced a change from 3.1 mils (79 µm) to 1.2 mils (30 µm) in surface profile.

Surface Profile Results For HS Scrubber Plate From Sour Water Unit With Process Fouling

Table 12 contains the surface profile information for the H2S scrubber plate from sour water unit with process fouling coupons. The abrasive-blasted coupons had a surface profile of 4.9 mils (124 µm) before and 3.6 mils (91 µm) after. UHP WJ uninhibited had surface profiles of 4.3 mils (109 µm) before and 3.8 mils (97 µm) after cleaning. A surface profile of 4.4 mils (112 µm) before and 4.0 mils (102 µm) after was measured on the UHP WJ inhibited coupons. The UHP WJ garnet coupons had a surface profile of 4.2 mils (107 µm) before and 3.5 mils (89 µm) after cleaning. As with the previous coupons, the UHP WJ garnet coupons closely resembled the abrasive-blasted coupons. The UHP WJ sodium bicarbonate coupons had a surface profile of 4.6 mils (117 µm) before cleaning and 4.0 mils (102 µm) after. As with all the previous coupon types, the flapper wheel coupons experienced the greatest change in surface profile with 4.8 mils (122 µm) before and 1.8 mils (46 µm) after cleaning.

Surface Profile Results For Heat Exchanger Shell in Propane service

The surface profile results are listed in Table 13 for the heat exchanger shell in propane service. The abrasive-blasted coupons reduced the surface profile from 4.8 mils (122 µm) before to 3.8 mils (97 µm) after cleaning. The surface profile of the UHP WJ uninhibited and UHP WJ inhibited coupons remained almost unchanged. The UHP WJ garnet coupons had a surface profile of 4.5 mils (114 µm) before and 4.2 mils (107 µm) after cleaning. The surface on the UHP WJ garnet coupons looked like an abrasive blasted surface. A surface profile of 4.6 mils (117 µm) before and 4.3 mils (109 µm) after cleaning was measured on the UHP WJ sodium bicarbonate coupons. The UHP WJ sodium bicarbonate coupons appeared whiter than the UHP WJ inhibited coupons but did not look like an abrasive-blasted surface. The flapper wheel coupon experienced the greatest change in surface profile with 4.6 mils (117 µm) before cleaning and 1.2 mils (30 µm) after cleaning.

WEIGHT LOSS RESULTS

Weight results are shown in Tables 8 through 13 along with surface profile information. The weight loss coupons measured 1 in. by 2 in. (2.54 cm by 5.08 cm) and were 1/16 in. to 7/16 in. (1.6 mm to 11.1 mm) thick. The majority of the coupons weighed in the 65 g range. One should only make comparisons in weight loss for each individual coupon type and not make comparisons between different coupon types because of the different thicknesses of the coupons.

Weight Loss Results For A-36[2] Mill-Scaled Coupons

The weight loss results are shown in Table 8 for the A-36[2] mill-scaled coupons. All the abrasive blasting and UHP WJ cleaning produced approximately the same amount of weight loss. The abrasive blasting and UHP WJ uninhibited cleaning also produced approximately the same amount of weight loss. The UHP WJ inhibited coupons experienced a weight loss of 0.29 g. A weight loss of 0.41 g was recorded for the UHP WJ garnet coupons. UHP WJ sodium bicarbonate had a weight loss of 0.24 g. The flapper wheel coupons did experience a weight loss about 10 times that of the other cleaning methods. The flapper wheel coupons did experience a large weight loss of 3.92 g. The nature of power tool cleaning lends itself to distortion of the steel (see Fig. 8). This is apparent with the large weight loss numbers for the flapper wheel; this amount of weight loss is not acceptable. The flapper wheel coupons were cleaned to the bare metal specifications so as to not unfairly treat power tool cleaning on the surface contaminant portion of our testing. The high weight loss numbers are a result of this conscious effort not to bias the testing away from power tool cleaning.

Weight Loss Results For A-285 [2] Grade 3 Mill-Scaled Steel

Table 9 shows the weight loss results for the A-285 [2] Mill_ scaled steel. Again, no significant difference in weight loss was detected between abrasive-blasted and UHP WJ coupons. The abrasive-blasted coupons experienced a weight loss of 0.47 g. The UHP WJ uninhibited and UHP WJ inhibited had about the same weight loss. UHP WJ garnet had a weight loss of 0.54 g. A weight loss of 0.30 g was measured for the UHP WJ sodium bicarbonate coupons. As with the A-36 [2] coupons, the flapper wheel showed the largest weight loss at 3.72 g.

Weight Loss Results For Heavily Rusted Water Service Pipe

The weight loss results for the heavily rusted water service pipe are listed in Table 10. The abrasive-b lasted and UHP WJ garnet coupons experienced a very similar weight loss. The UHP WJ sodium bicarbonate and UHP WJ uninhibited coupons had nearly identical weight loss. The UHP WJ inhibited coupons experienced a weight loss of 0.88 g. The flapper wheel showed a weight loss of 10.18 g. The pits were ground out of the flapper wheel coupons.

Weight Loss Results For Intact Coating on Water service Pipe

Table 11 shows the weight loss and surface profile results for intact coating on water service pipe coupons. The UHP WJ uninhibited, UHP WJ inhibited, and UHP WJ garnet all experienced greater weight loss than abrasive blasting. The abrasive-blasted coupons experienced a weight loss of 0.69 g. A weight loss of 0.86 g was recorded for the UHP WJ uninhibited coupons. The UHP WJ inhibited coupons experienced a weight loss of 0.91 g. The UHP WJ garnet coupons experienced a weight loss of 1.26 g. A weight loss of 0.44 g was recorded for the UHP WJ sodium bicarbonate coupons. As with all the previous cases, the flapper wheel coupons experienced a large weight loss at 6.92 g.

Weight Loss Results For H_2S Scrubber Plate From Sour Water Unit With Process Fouling

The weight loss results for the H_2S scrubber plate from sour water unit with process fouling coupons are shown in Table 12. The abrasive-blasted weight loss was greater than the UHP WJ inhibited, UHP WJ garnet, and UHP WJ sodium bicarbonate weight loss. However, the UHP WJ uninhibited weight loss was over twice that of abrasive blasting. This is probably because this plate was heavily rusted. The abrasive-blasted coupons had a weight loss of 0.82 g. The UHP WJ uninhibited coupons had a weight loss of 1.79 g. A weight loss of 0.42 g was recorded for the UHP WJ inhibited coupons. The UHP WJ garnet coupons recorded a weight loss of 0.64 g. A weight loss of 0.38 g was measured for the UHP WJ sodium bicarbonate coupons. Again, the flapper wheel coupons experienced a large weight loss at 5.54 g.

Weight Loss Results For Heat Exchanger Shell in Propane service

Table 13 contains weight loss information for the heat exchanger shell in propane service. Abrasive-blasted and UHP WJ uninhibited coupons experienced almost the same weight loss. The UHP WJ inhibited and UHP WJ sodium bicarbonate coupons had the same weight loss at 0.37 g. A weight loss of 0.49 g was recorded for the UHP WJ garnet coupons. As with all cases in the testing, the flapper wheel coupons experience the greatest weight loss at 7.86 g.

CONCLUSIONS

Abrasive blasting did a fine job for initial cleaning to remove mill scale and provided an initial surface profile. The process did provide good visual cleanliness, but deposits of rust could be found after the coupons were boiled. Small packets of rust remained on some coupons. This hidden rust was not visible to the naked eye, but rust could be found on some of the photomicrographs. Abrasive blasting also did not leave the surface free of surface contaminants. Abrasive blasting was an effective way of removing sulfates; however 50% of the time it did not remove chlorides to safe levels. The weight loss for abrasive-blasted steel was no higher than the UHP WJ methods; very little steel was removed by abrasive blasting. A fuzzy interface between the epoxy and metal occurred while abrasive blasting. It was created by the distortion of the metal that occurs while abrasive blasting. Also, the FTIR detected silica and epoxy coating remaining on abrasive-blasted coupons.

UHP WJ uninhibited cleaned steel to very low levels of sulfates and chlorides. UHP WJ uninhibited did not provide a surface profile and should only be used on equipment or steel that has been abrasive blasted. Photomicrographs of the edge profile showed clean steel with very small areas of rust remaining. This rust originated from flash rusting, which occurred after the coupon was cleaned. Weight loss was comparable to that of abrasive blasting. The FTIR detected nothing of interest on the UHP WJ uninhibited coupons.

UHP WJ inhibited did provide a surf ace free of chlorides; however, UHP WJ inhibited did not remove sulfates to safe levels 33% of the time. This may have been caused by using a defective inhibitor. None of the other UHP WJ methods showed problems removing sulfates. Boiling UHP WJ inhibited coupons showed very little amounts of rust sediment. Edge profile photos of UHP WJ inhibited coupons showed no visible rust and the steel was very clean. No significant surface profile changes were experienced with UHP WJ inhibited. Weight loss was comparable to abrasive blasting. The FTIR detected phosphates on the UHP WJ inhibited coupons.

UHP WJ garnet left a surface with safe levels of sulfates and chlorides. The edge profiles were very clean and did not show any remaining rust. Boiling coupons showed very little rust sediment was present. The process did modify the surface profile similar to abrasive blasting. The weight loss information on UHP WJ garnet showed very little steel was removed from the surface.

UHP WJ sodium bicarbonate left the steel clean of sulfates. The phosphate and nitrate levels were higher on the UHP WJ sodium bicarbonate coupons because the inhibitor was applied with a sprayer; therefore the application of inhibitor with a sprayer produced higher levels of phosphates and nitrates. However, injection of inhibitor at pump suction did produce much lower levels phosphates and nitrates. on one occasion, chloride levels were outside our safe levels for the UHP WJ sodium bicarbonate coupons. Boiling coupons did not show any significant levels of trapped rust. No surface profile was created and normal weight loss could be expected with this method.

Power tool cleaning to bare metal (SSPC-SP 11-87T) provided very low levels of sulfates and chlorides. Boiling coupons showed very little amounts of rust sediment. Without a doubt, power tool cleaning to a SSPC-SP 3 would have produced much higher levels of sulfates and chlorides. The surface of flapper wheel cleaned samples was very clean. Significant changes in the surface profile occurred. The weight loss was excessive and made this method undesirable; there was a tendency to remove too much metal and distort the metal.

The data generated by cleaning with UHP WJ sodium bicarbonate and UHP WJ garnet methods were generated using water at 35,000 psi (241,325 kPa) . The effectiveness of these methods was a result of the combination of the UHP WJ and abrasive. one should not assume that using sodium bicarbonate and garnet under other operating conditions and means of propulsion would necessarily produce similar results.

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TABLE 1
SURFACE CONTAMINANT RESULTS FOR A-36[2] MILL-SCALED STEEL (<100'S)

Surface Preparation Methods	Sulfates ($\mu g/cm^2$)	Phosphates ($\mu g/cm^2$)	Chlorides ($\mu g/cm^2$)	Nitrates ($\mu g/cm^2$)
Uncleaned	40	0	2	0
Abrasive Blasted	3	0	2	6
UHP WJ Uninhibited	0	0	1	0
UHP WJ Inhibited	1	3	3	4
UHP WJ Garnet	4	3	0	6
UHP WJ Sodium Bi-carbonate	4	54	3	110
Flapper Wheel	1	0	1	2

TABLE 2
SURFACE CONTAMINANT RESULTS FOR A-285[2] GRADE 3 MILL-SCALED STEEL (100'S)

Surface Preparation Methods	Sulfates ($\mu g/cm^2$)	Phosphates ($\mu g/cm^2$)	Chlorides ($\mu g/cm^2$)	Nitrates ($\mu g/cm^2$)
Uncleaned	5	0	4	0
Abrasive Blasted	5	1	3	11
UHP WJ Uninhibited	0	0	1	1
UHP WJ Inhibited	4	4	1	7
UHP WJ Garnet	1	6	1	3
UHP WJ Sodium Bi-carbonate	3	64	0	107
Flapper Wheel	0	0	0	0

NOTE: A-285[2] is a new specification for a material formally known as A-70.[2] The A-70[2] ASTM specification was abolished in 1927.[2]

TABLE 3
SURFACE CONTAMINANT RESULTS FOR HEAVILY RUSTED WATER SERVICE PIPE (200'S)

Surface Preparation Methods	Sulfates ($\mu g/cm^2$)	Phosphates ($\mu g/cm^2$)	Chlorides ($\mu g/cm^2$)	Nitrates ($\mu g/cm^2$)
Uncleaned	5	1	28	6
Abrasive Blasted	2	2	32	1
UHP WJ Uninhibited	1	0	1	1
UHP WJ Inhibited	15	5	1	7
UHP WJ Garnet	2	6	0	8
UHP WJ Sodium Bi-carbonate	9	62	1	124
Flapper Wheel	0	0	0	0

TABLE 4
SURFACE CONTAMINANT RESULTS FOR INTACT COATING ON WATER SERVICE PIPE (300'S)

Surface Preparation Methods	Sulfates ($\mu g/cm^2$)	Phosphates ($\mu g/cm^2$)	Chlorides ($\mu g/cm^2$)	Nitrates ($\mu g/cm^2$)
Uncleaned	8	0	6	4
Abrasive Blasted	4	2	1	2
UHP WJ Uninhibited	0	0	1	1
UHP WJ Inhibited	1	19	0	7
UHP WJ Garnet	0	3	0	5
UHP WJ Sodium Bi-carbonate	11	66	0	122
Flapper Wheel	0	0	1	0

TABLE 5
SURFACE CONTAMINANT RESULTS FOR H_2S SCRUBBER PLATE FROM SOUR WATER UNIT WITH PROCESS FOULING (400'S)

Surface Preparation Methods	Sulfates ($\mu g/cm^2$)	Phosphates ($\mu g/cm^2$)	Chlorides ($\mu g/cm^2$)	Nitrates ($\mu g/cm^2$)
Uncleaned	39	0	12	0
Abrasive Blasted	7	0	8	1
UHP WJ Uninhibited	0	0	0	0
UHP WJ Inhibited	44	8	1	1
UHP WJ Garnet	3	2	1	3
UHP WJ Sodium Bi-carbonate	6	70	11	120
Flapper Wheel	0	0	1	0

TABLE 6
SURFACE CONTAMINANT RESULTS FOR HEAT EXCHANGER SHELL IN PROPANE SERVICE (500'S)

Surface Preparation Methods	Sulfates ($\mu g/cm^2$)	Phosphates ($\mu g/cm^2$)	Chlorides ($\mu g/cm^2$)	Nitrates ($\mu g/cm^2$)
Uncleaned	7	0	17	0
Abrasive Blasted	4	0	31	3
UHP WJ Uninhibited	0	0	0	0
UHP WJ Inhibited	24	8	1	6
UHP WJ Garnet	0	7	0	6
UHP WJ Sodium Bi-carbonate	2	39	0	204
Flapper Wheel	0	0	0	1

TABLE 7
RESULTS OF RESIDUE ANALYSIS FROM BOILING EXTRACTION COUPONS

Surface Preparation Methods	Sample Bottle Number	Residue ($\mu g/cm^2$)
Uncleaned	534	121
Abrasive Blasted	573	50
UHP WJ Uninhibited	572	39
UHP WJ Inhibited	553	27
UHP WJ Garnet	529	17
UHP WJ Sodium Bicarbonate	512	8
Flapper Wheel	503	27

TABLE 8
SURFACE PROFILE AND WEIGHT LOSS RESULTS FOR A-36[2] MILL-SCALED STEEL (<100'S)

Surface Preparation Methods	Surface Profile Before (mils)	Surface Profile After (mils)	Weight Loss (g)
Abrasive Blasted	1.9	2.5	0.37
UHP WJ Uninhibited	2.3	2.5	0.36
UHP WJ Inhibited	2.5	2.8	0.29
UHP WJ Garnet	2.6	2.2	0.41
UHP WJ Sodium Bi-carbonate	2.1	1.9	0.24
Flapper Wheel	2.5	1.3	3.92

TABLE 9
SURFACE PROFILE AND WEIGHT LOSS RESULTS FOR A-285[2] GRADE 3 MILL-SCALED STEEL (100'S)

Surface Preparation Methods	Surface Profile Before (mils)	Surface Profile After (mils)	Weight Loss (g)
Abrasive Blasted	2.6	2.2	0.47
UHP WJ Uninhibited	1.7	1.8	0.43
UHP WJ Inhibited	1.9	1.9	0.41
UHP WJ Garnet	2.4	2.1	0.54
UHP WJ Sodium Bi-carbonate	2.2	1.8	0.30
Flapper Wheel	2.5	1.2	3.72

Note: A-285[2] is a new specification for a material formally known as A-70.[2] The A-70[2] ASTM specification was abolished in 1927.[2]

TABLE 10
SURFACE PROFILE AND WEIGHT LOSS RESULTS FOR HEAVILY RUSTED WATER SERVICE PIPE (200'S)

Surface Preparation Methods	Surface Profile Before (mils)	Surface Profile After (mils)	Weight Loss (g)
Abrasive Blasted	5.1	3.8	0.95
UHP WJ Uninhibited	4.0	3.6	0.59
UHP WJ Inhibited	3.8	3.9	0.88
UHP WJ Garnet	4.1	3.2	0.97
UHP WJ Sodium Bi-carbonate	4.0	2.7	0.60
Flapper Wheel	4.6	2.1	10.18

TABLE 11
SURFACE PROFILE AND WEIGHT LOSS RESULTS FOR INTACT COATING ON WATER SERVICE PIPE (300'S)

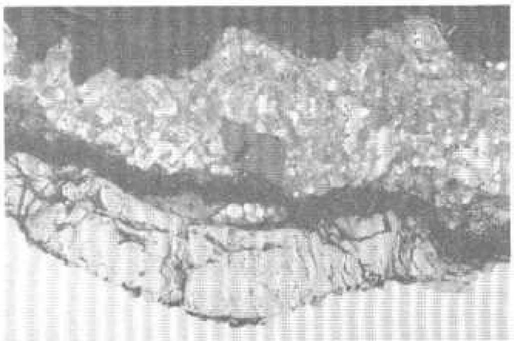
Surface Preparation Methods	Surface Profile Before (mils)	Surface Profile After (mils)	Weight Loss (g)
Abrasive Blasted	3.6	3.5	0.69
UHP WJ Uninhibited	2.6	3.6	0.86
UHP WJ Inhibited	2.2	3.5	0.91
UHP WJ Garnet	2.0	3.1	1.26
UHP WJ Sodium Bi-carbonate	3.0	3.0	0.44
Flapper Wheel	3.1	1.2	6.92

TABLE 12
SURFACE PROFILE AND WEIGHT LOSS RESULTS FOR H_2S SCRUBBER PLATE FROM SOUR WATER UNIT WITH PROCESS FOULING (400'S)

Surface Preparation Methods	Surface Profile Before (mils)	Surface Profile After (mils)	Weight Loss (g)
Abrasive Blasted	4.9	3.6	0.82
UHP WJ Uninhibited	4.3	3.8	1.79
UHP WJ Inhibited	4.4	4.0	0.42
UHP WJ Garnet	4.2	3.5	0.64
UHP WJ Sodium Bi-carbonate	4.6	4.0	0.38
Flapper Wheel	4.8	1.8	5.54

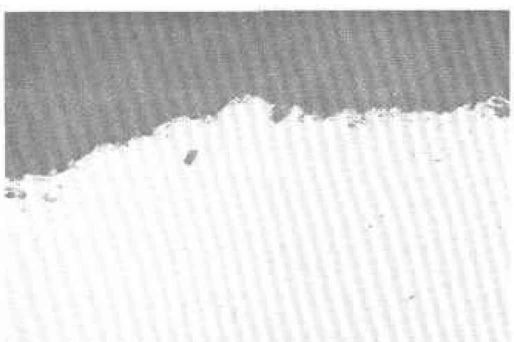
TABLE 13
SURFACE PROFILE AND WEIGHT LOSS RESULTS FOR HEAT EXCHANGER SHELL IN PROPANE SERVICE (500'S)

Surface Preparation Methods	Surface Profile Before (mils)	Surface Profile After (mils)	Weight Loss (g)
Abrasive Blasted	4.8	3.8	0.42
UHP WJ Uninhibited	4.4	4.2	0.43
UHP WJ Inhibited	4.2	4.0	0.37
UHP WJ Garnet	4.5	4.2	0.49
UHP WJ Sodium Bi-carbonate	4.6	4.3	0.37
Flapper Wheel	4.6	1.2	7.86

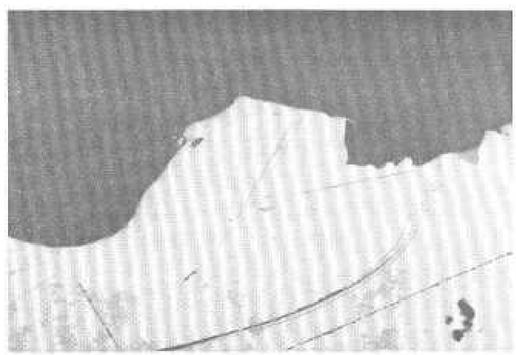


X300 —— 40 μm (1.6 mils)
FIGURE 9 - Intact coating on water service pipe before cleaning. Note rust in gray area above the base metal.

X300 —— 40 μm (1.6 mils)
FIGURE 10 - Intact coating on water service pipe before cleaning. A representative photo of the surface before cleaning.

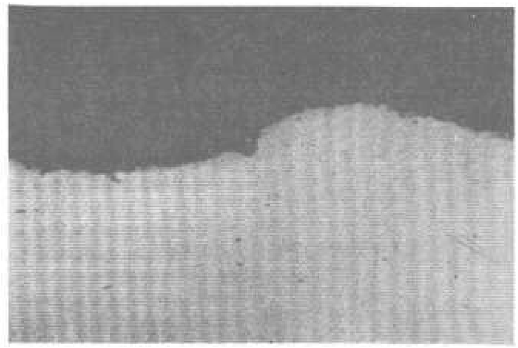


X300 —— 40 μm (1.6 mils)
FIGURE 11 - Intact coating on water service pipe cleaned by abrasive blasting.

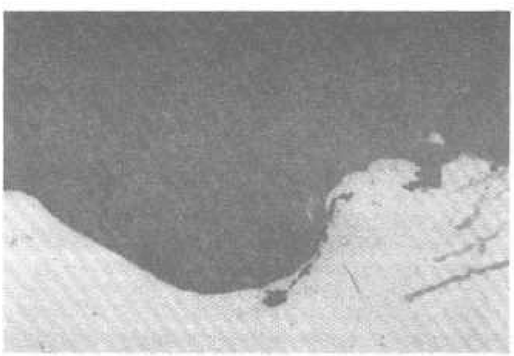


X300 —— 40 μm (1.6 mils)
FIGURE 12 - Intact coating on water service pipe cleaned by UHP WJ uninhibited. Gray area on right-hand side is a small piece of rust.

X300 —— 40 μm (1.6 mils)
FIGURE 13 - Intact coating on water service pipe cleaned by UHP WJ inhibited. Note the clean crevice in the center of the photomicrograph.

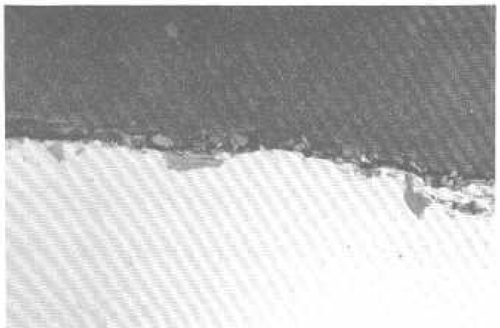


X300 —— 40 μm (1.6 mils)
FIGURE 14 - Intact coating on water service pipe cleaned by UHP WJ garnet.

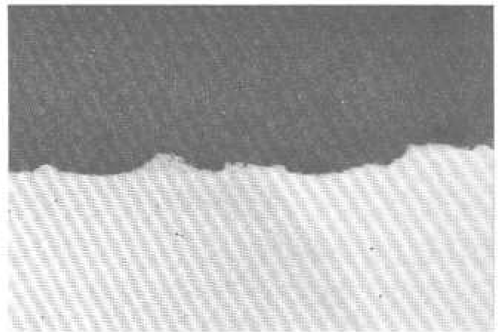


X300 —— 40 μm (1.6 mils)
FIGURE 15 - Intact coating on water service pipe cleaned by UHP WJ sodium bicarbonate.

X300 —— 40 μm (1.6 mils)
FIGURE 16 - Intact coating on water service pipe cleaned by flapper wheel.

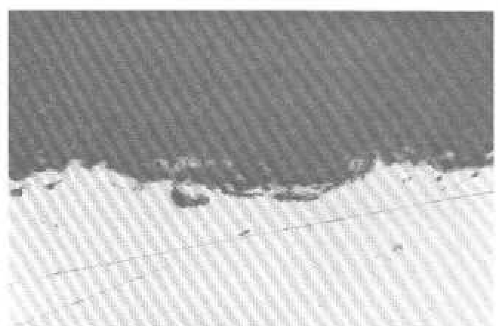


X300 —— 40 μm (1.6 mils)
FIGURE 17 - A-36[2] mill-scaled steel cleaned by abrasive blasting.

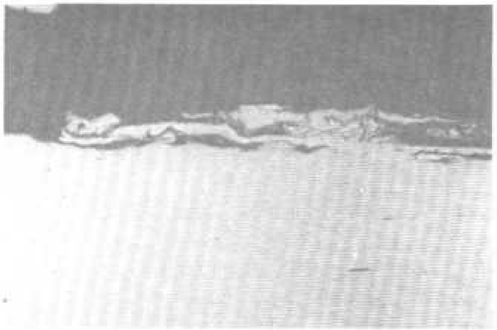


X300 —— 40 μm (1.6 mils)
FIGURE 18 - A-36[2] mill-scaled steel cleaned by UHP WJ uninhibited.

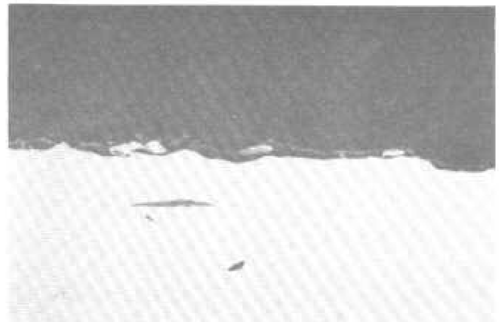
X300 —— 40 μm (1.6 mils)
FIGURE 19 - A-36[2] mill-scaled steel cleaned by UHP WJ inhibited. Note how the water cleaned deep into the crack.



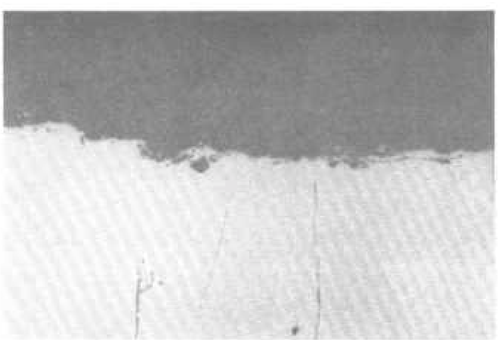
X300 —— 40 μm (1.6 mils)
FIGURE 20 - A-285[2] mill-scaled steel cleaned by abrasive blasting. No rust layer is present.



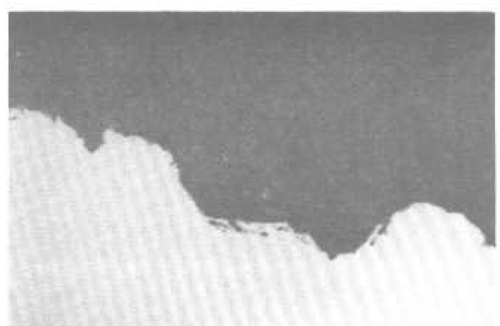
X300 —— 40 μm (1.6 mils)
FIGURE 21 - A-285[2] mill-scaled steel cleaned by UHP WJ uninhibited.



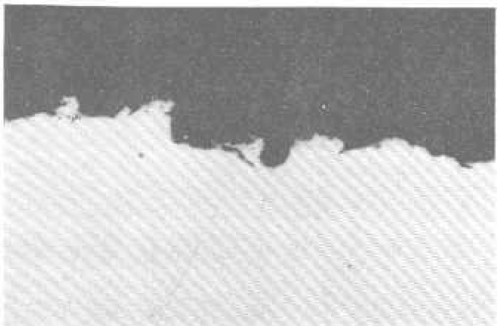
X300 —— 40 μm (1.6 mils)
FIGURE 22 - A-285[2] mill-scaled steel cleaned by UHP WJ inhibited. Lamination layers consist of aluminum, silicon, iron, and mainly manganese.



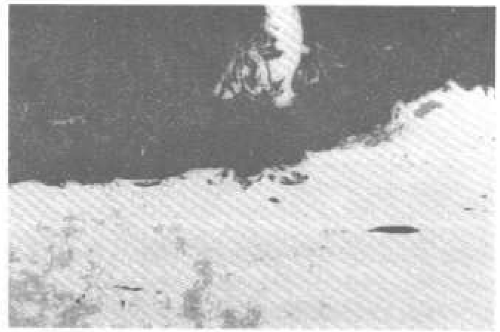
X300 —— 40 μm (1.6 mils)
FIGURE 23 - Heavily rusted pipe in water service cleaned by abrasive blasting. Note: a light layer of rust was remaining on this coupon.



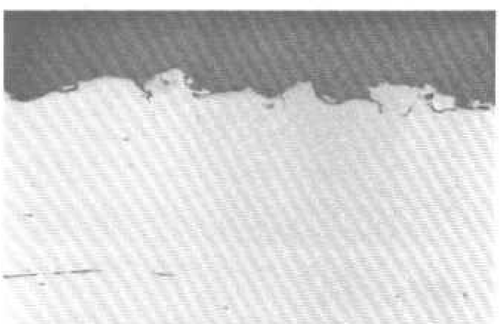
X300 —— 40 μm (1.6 mils)
FIGURE 24 - Heavily rusted pipe in water service cleaned by UHP WJ uninhibited.



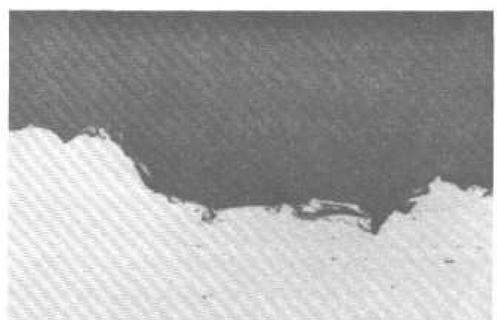
X300 —— 40 μm (1.6 mils)
FIGURE 25 - Heavily rusted pipe cleaned by UHP WJ inhibited.



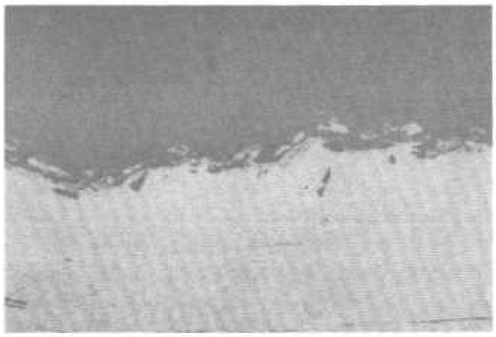
X300 —— 40 μm (1.6 mils)
FIGURE 26 - H_2S scrubber plate cleaned by abrasive blasting.



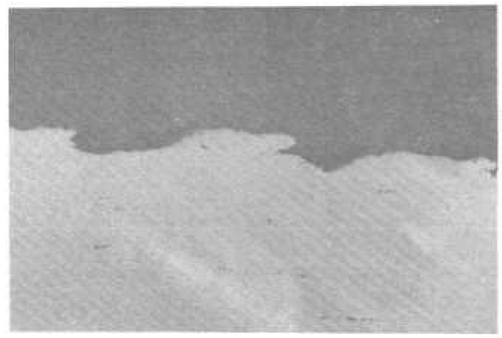
X300 —— 40 μm (1.6 mils)
FIGURE 27 - H_2S scrubber plate cleaned by UHP WJ uninhibited.



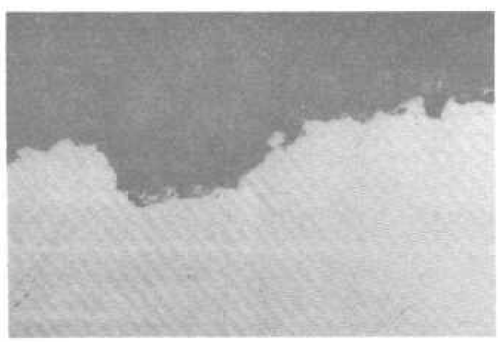
X300 —— 40 μm (1.6 mils)
FIGURE 28 - H_2S scrubber plate cleaned by UHP WJ inhibited.



X300 —— 40 μm (1.6 mils)
FIGURE 29 - Heat exchanger shell cleaned by abrasive blasting.



X300 —— 40 μm (1.6 mils)
FIGURE 30 - Heat exchanger shell cleaned by UHP WJ uninhibited.



X300 —— 40 μm (1.6 mils)
FIGURE 31 - Heat exchanger shell cleaned by UHP WJ inhibited.

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