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## **Rouging of Stainless Steel in WFI and High Purity Water Systems**

By  
John C. Tverberg  
Trent Tube

And  
James A. Ledden  
Pharmacia and Upjohn

### **Abstract**

Stainless steel is used in WFI or High Purity water systems for its corrosion resistance. Under some conditions the stainless steel appears to be corroding, forming orange, red, magenta or black oxides. Analysis of the different oxides and the stainless steel passive layer under the rouge reveals that three different types of rouge may be forming depending on the nature of the oxide and damage to the underlying passive layer. Basically, rouge is iron oxide with or without water of hydration and different valence levels for iron. Two types of rouge arise from the stainless steel surface interacting with the environment, and the third type has a secondary origin.

### **Introduction**

Red deposits in WFI and High Purity water systems have been a problem since stainless steel was introduced as a piping system. Electropolishing was thought to be a solution to the problem, but rouging, or the powdery red, magenta, orange or yellow orange persisted. In hot water systems a black deposit became commonplace, sometimes powdery, sometimes glossy. Much conjecture has been offered, but little in the area of hard physical data.

In late 1997, a piping system at Pharmacia and Upjohn, Kalamazoo, MI was removed after 15 years service. This system had both WFI and High Purity water components and the piping showed extensive rouging. It had operated at 150° F (65° C), been in service for 15 years and had never been cleaned. The water flow rate was 38 gallons per minute velocity 5 feet per second. This provided an ideal opportunity for an investigative study of the rouge. These tubes are identified as "Sample Set # 1".

A specimen with a different appearance red rouge was obtained from another pharmaceutical company. This tubing was mechanically polished without chemical passivation. Service time was several months, but red rouge was beginning to form. This tube is identified as "Sample Set # 2".

Another sample was obtained from a third source from a WFI steam line operating at 450° F (235° C). This tube had been in service for several years and the black, glossy oxide was stable. This tube is identified as "Sample Set # 3".

A second high temperature steam environment was brought to our attention, from yet a different site, in which the black oxide was powdery black. No specimens were obtained, so only the visual observations at the site were recorded.

The questions we faced were: Are the oxides related? What is the composition of the oxides? Is the stainless steel tubing part of the reaction? And what is the mechanism of formation?

To answer these questions we used some of the most powerful metallurgical evaluation tools available including the scanning electron microscope (SEM), energy dispersive spectroscopy (EDS) and x-ray photoelectron spectroscopy (XPS) also called ESCA or electron spectroscopy for chemical analysis. Auger electron spectroscopy (AES) was considered, but XPS was selected because of the ability to identify metal valence states and molecular type. No single analytical method by itself was sufficient to answer the questions, but when combined a systematic picture began to emerge that answered most of our questions.

### **Investigative Methodology**

Specimens were removed from strategic positions whenever possible. Specimens were chosen based on rouge color, location and any anomaly that was apparent. In general, an orbital weld was chosen adjacent to a parent metal specimen. Only one longitudinal factory weld was sectioned.

#### **Scanning Electron Microscopy:**

Scanning electron microscopy, or SEM, allows detailed examination of the topography because of its inherent high depth of field and magnification. The depth of field is important since both peaks and valleys are in focus. Because of the electron charging of the surface, it is possible to differentiate between organic and inorganic surface compounds.

#### **Energy Dispersive Spectroscopy:**

Energy dispersive spectroscopy is an adjunct to the SEM and allows very small spot analyses. Compositions obtained usually are expressed in weight percent. They should not be taken as absolute, but rather to give the approximate composition of the material being analyzed. Both the rouge and the metal were analyzed. The rouge composition was analyzed over a large surface area to minimize variations in the rouge layer.

#### **X-Ray Photoelectron Spectroscopy:**

X-Ray photoelectron spectroscopy uses soft x-rays to irradiate the surface and the emitted electrons are analyzed for energy response. Since each element and compound has a unique set of binding energies it is possible to identify the element and its chemical state. By bombarding the surface with high energy argon ions the surface can be blasted away and, with another analysis, it is possible to obtain a depth profile of the change in composition. Both the rouge and the metal were analyzed. This technique allowed us to identify the chemical state of each major element, however the spot size was so small that the overall composition of the rouge was suspect.

## **Results**

### **Scanning Electron Micrographic Examination:**

Examination of the different rouged specimens showed a significant variation with a change in color, surface conditioning, and operating environment. All examination was at 450X.

#### **Sample Set #1:**

SEM examination of a "silver" surface in the WFI loop shows isolated oxide particles. These particles usually collect on inclusion pits within the grain or on grain boundaries. They are small, spherical particles that are widely separated as seen in Figure 1. The orbital welds have the particles attached to the ridges on the welds. The longitudinal factory weld appeared to have fewer particles than the base metal, possibly because the weld had fewer inclusions.

From the high purity loop of the same system, the magenta, or dark red surface, had a very thin layer of oxide, under which the electropolished finish is clearly visible. SEM examination shows a denser population of spherical oxide particles of smaller diameter than those on the silver surface. Location is not site specific as on the silver surface, but rather evenly distributed over the entire surface as seen in Figure 2.

The orange surface may be the most interesting. Here the spherical particles are deposited heavily over the entire surface, layer upon layer like grains of sand on the beach. The sphere size appears smaller than those on the silver surface, but larger than the magenta surface. Figure 3 shows the surface appearance. The orbital welds have the same layered appearance, with the oxides following the contours of the weld surface.

When the surface oxides are removed with detergent in a water bath using ultrasonic energy to jar the oxides loose, the surface looks the same as an electropolished surface. There is no evidence of pitting, crevice or other corrosion of the surface.

#### **Sample Set # 2:**

Examination of a section of tubing from another system, which used mechanically polished and non-passivated material, had a different appearance as in Figure 4. The oxides appeared to grow on the surface of the metal as blisters. In those areas where the blisters were knocked loose, bare metal was visible with areas of bright metal on the bare spots, similar to a stainless steel surface undergoing crevice corrosion. Removal of the oxide was difficult, especially in the non-blistered areas.

#### **Sample Set # 3:**

The third specimen came from a high temperature, high purity electropolished steam line operating at 350° F (175° C). Visually, this specimen had a glossy gray-black surface. The SEM showed distinct crystals on the surface of a crystalline base as shown in Figure 5. These crystals match the octahedral and dodecahedral shape for magnetite crystals. They appear to be growing together in some areas to produce a heavier film. The underlying crystal base is continuous and appears to be the initial stage of this type of rouge development.

### **Energy Dispersive Spectroscopic Analysis:**

Energy Dispersive Spectroscopy, or EDS, is often used in conjunction with SEM evaluation of the surface. It is sometimes called microprobe analysis because of its ability to measure a small spot. In this evaluation we found EDS to be the most useful in identifying the elements present in the oxide films. Keep in mind that the composition values obtained should not be taken as absolute, especially the low atomic weight and trace elements. The main advantage of EDS is its ability to indicate what elements are present in a small spot.

### **Sample Set #1:**

Table I is a compilation of the analyses by color from the various specimens of the group of tubes taken from the 15 year old WFI/HP system. The values reported are the average of several different areas. Also included is an analysis of the bare metal and the orbital weld metal.

Table I: Rouge Composition According to Color and Base and Orbital Weld Metal

Color	Chromium	Nickel	Molybdenum	Manganese	Silicon	Iron
Silver	19.8	10.1	2.3	1.9	0.5	65.4
Orange	20.2	9.1	2.1	1.3	0.3	67.1
Magenta	20.3	9.9	2.3	1.7	0.4	65.4
Base Metal	19.2	10.6	2.2	1.7	0.5	65.8
Weld Metal	19.8	10.1	2.2	1.8	0.4	65.6

These data indicate that the composition of the rouge closely matches that of the base metal and orbital weld metal. This is not typical of corroding stainless steel in which the predominant oxides are iron and with some chromium and essentially no nickel, molybdenum or silicon.

### **Sample Set # 2:**

Table II is an analysis of the rouge from the second system in which the tubing was mechanically polished and non-passivated. The data are from a single analysis.

Table II: Rouge and Base Metal Composition of Non-Passivated Mechanically Polished Tube

Location	Cr	Ni	Mo	Mn	Fe	Si	Cl	K	Ca	Al	O	C
Red Oxide	19.6	5.4	1.0	3.3	51.1	2.1	4.8	0.6	0.6	0.8	9.2	1.6
Base Metal	23.3	6.3	1.1	4.6	63.4	1.3	-	-	-	-	-	-

The rouge is predominately iron oxide and chromium oxide. The surprise is the chlorine, and its concentration. The high carbon most likely is due to occluded carbon dioxide. The rouge composition is very similar to that of corroding stainless steel in the presence of chlorides.

### **Sample Set # 3:**

Table III is an analysis of the black oxide from the electropolished steam line. The data are from a single analysis.



Table III: Black Oxide Analysis From an Electropolished Steam System

Location	Cr	Ni	Mo	Mn	Si	Al	Ca	C	Fe	O
Black Oxide	27.2	3.9	1.3	3.5	0.9	0.2	0.2	1.4	41.9	19.6
Base Metal	24.6	7.0	1.3	4.2	1.	-	-	-	61.9	-

This analysis nearly matches the chromium/iron ratio for an electropolished stainless steel surface. The high oxygen content indicates an oxide on the surface with some occluded carbon dioxide.

#### X-Ray Photoelectron Spectrographic Analysis:

The absolute analyses from XPS were somewhat disappointing in that they did not show trends, rather were more scattered. All composition values are reported in atomic percent rather than weight percent. This is endemic to the technique since the software is set up to provide atomic percent. For stainless steel the main alloying elements expressed in atomic percent are very close to the values in weight percent. The values for oxygen, carbon, chlorine and other non-metals are quite different in weight percent. The main advantage of XPS in this study is identification of the molecular species in the rouge layers. This feature is extremely important in that it allows a better understanding of the oxidation process involved in the rouging process.

#### Sample Set #1:

Table IV presents the analytical data and Table V identifies the molecular species identified in the rouge or on the surface.

Table IV: Composition of Rouge/Metal Using XPS

	O	F	Cr	Fe	Ni	Mo	Si	C
Silver	27.5	0.6	6.6	0.3	0	0.13	1.2	63.6
Orange	33.5	1.4	7.9	1.1	0.02	0.15	1.4	51.7
Magenta	35.3	0.1	8.0	5.8	1.1	0.28	0.25	48.4
Bare Metal	43.3	2.3	13.8	2.5	0.3	0.30	0.2	36.4

Table V: Molecular Species in Rouge and on the Metal Surface

	F	Si	Cr	Fe	Ni	Mo
Silver	Teflon	SiO <sub>3</sub>	Cr <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub> /Fe <sup>0</sup>	Int. Met. Cpd*	MoO <sub>3</sub>
Orange	Teflon	SiO <sub>2</sub> /SiO <sub>3</sub>	Cr <sub>2</sub> O <sub>3</sub>	FeO(OH)	Int. Met. Cpd	MoO <sub>3</sub>
Magenta	Teflon	SiO <sub>3</sub> /Si <sup>0</sup>	Cr <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub> /Fe <sup>0</sup>	Int. Met. Cpd	MoO <sub>3</sub> /Mo <sup>0</sup>
Bare Metal	Teflon	SiO <sub>3</sub>	Cr <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub> /Fe <sup>0</sup>	Ni <sup>0</sup>	MoO <sub>3</sub>

\*Int.Met.Cpd = Intermetallic Compound

Teflon's presence was a surprise and its source was traced to diaphragms and gaskets. The orange color is due to hydrated ferrous oxide, while oxides of the other metals essentially had the same composition for all color forms. The main contributor to the magenta color is the ferric oxide or hematite. It is significant that metallic iron (valence 0) was present in the magenta film, since this indicates unoxidized iron. In previous studies<sup>1</sup> we showed that during passivation the chromium needed to be oxidized before the iron would complete its oxidation.

No free chromium was detected. In another study<sup>2</sup>, in which the electropolished film was caused to form gold and blue colors, we found that the gold color represented the stage in which no metallic iron was present, and both the chromium and iron were completely oxidized. When the color shifted to blue the molecular form of iron changed to  $\text{Fe}_2\text{O}_3\cdot\text{FeO} + \text{Fe}_2\text{O}_3$  or  $\text{Fe}_3\text{O}_4 + \text{Fe}_2\text{O}_3$ . In the case of the magenta film we found no evidence of the mixed oxide, only  $\text{Fe}_2\text{O}_3$  with some elemental iron. This indicates the mechanism is not *in situ* oxidation, but rather redeposition of oxide particles. Silicon is somewhat of a mystery since it changes valence from 0, +4, +6 with no seeming predictability. Silicon may ultimately play a role in the formation of the oxides and in the passivation and oxidation process. Both nickel and molybdenum appear to follow common oxidation mechanisms.

### Sample Set #2:

The surface had both red oxides and areas with no oxides, the red oxide predominating. Following the initial analysis the sample was passivated in 20% nitric acid for 30 minutes at 130° F (55° C). The results of the analyses are included in Table VI and the molecular species are in Table VII.

Table VI: Composition of Red Rouge from Non-Passivated Mechanically Polished Tube

	O	Cr	Fe	Ni	Mo	Si	Cl
Bare Metal, AR <sup>1</sup>	70.8	7.7	7.4	0.6	0	9.2	4.3
Red Oxide, AR	69.9	3.9	4.8	0.4	0	17.0	3.9
Bare Metal, AP <sup>2</sup>	70.9	17.3	4.8	0.7	0.7	5.0	0.7
Red Oxide, AP	71.0	13.0	3.0	0.3	0.6	10.9	1.2

1. AR = As Received

2. AP = After Passivation

Table VII: Molecular Species of Elements in Red Oxide and Bare Metal

	Cr	Fe	Ni	Si	Cl
Bare Metal, AR <sup>1</sup>	$\text{Cr}_2\text{O}_3$	$\text{Fe}_2\text{O}_3 + \text{Fe}^0$	$\text{Ni}(\text{OH})_2 + \text{Ni}^0$	$\text{SiO}_3$	Chloride
Red Oxide, AR	$\text{Cr}_2\text{O}_3$	$\text{Fe}_2\text{O}_3$	$\text{Ni}(\text{OH})_2$	$\text{SiO}_3$	Chloride
Bare Metal, AP <sup>2</sup>	$\text{Cr}_2\text{O}_3$	$\text{Fe}_2\text{O}_3 + \text{Fe}^0$	$\text{Ni}^0$	$\text{SiO}_3$	Chloride
Red Oxide, AP	$\text{Cr}_2\text{O}_3$	$\text{Fe}_2\text{O}_3 + \text{Fe}^0$	$\text{Ni}(\text{OH})_2 + \text{Ni}^0$	$\text{SiO}_3$	Chloride

1. AR = As Received

2. AP = After Passivation

The significance of these values is the presence of chloride in the corrosion layer and on the metal, *even after passivation*. Normally, passivation removes any chloride if it is a surface occlusion, but not if it has reacted with the base metal and is locked into the crystal lattice. We can be fairly certain that the chloride had a direct effect in the corrosion mechanism by forming the soluble chromous chloride. The other startling fact is the nickel is present as the hydroxide. This is the only time we have seen this phenomenon. The fact that no elemental chromium was found indicates that it may be tied up as the chloride or totally dissolved. And the iron, present as the ferric oxide, or hematite, accounts for the red rust color.

**Sample Set 3:**

This sample came from an electropolished tube that had been in a steam environment. Both the XPS analytical data and the chemical state data are presented in Table VIII.

Table VIII: Composition and Molecular State of Glossy Black Oxide Layer

	O	Na	Ca	Cr	Fe	Ni
Composition	55.8	0.7	0.6	16.7	25.4	0.6
Molecular State	Mixed Oxides	Sodium Silicate	Complex Oxides	Cr <sub>2</sub> O <sub>3</sub>	Fe <sub>3</sub> O <sub>4</sub>	NiO

Several significant observations can be made from these data. First, the iron is present as magnetite, Fe<sub>3</sub>O<sub>4</sub>, which accounts for the black color. Second, the percentage of iron is higher than the chromium, probably because of diffusion of the additional iron needed to form the complex Fe<sub>3</sub>O<sub>4</sub> molecule. Third, both calcium and sodium are present which normally do not appear in WFI or High Purity water systems. Neither of these elements are thought to have any effect on the formation of magnetite.

### Proposed Mechanisms

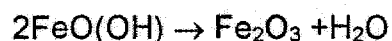
In all of these rouge formations, the color comes from the presence of the various iron oxides. The other oxides will not offer a major color effect unless they become quite thick. Therefore, the formation of the iron oxides is essential to an understanding the mechanism of rouge formation.

The lowest valence state is the orange oxide, identified here as FeO(OH) or hydrated ferrous oxide. According to Dana<sup>3</sup> this form corresponds to the mineral Limonite, which is yellowish brown to orange in color. The formation can be chemically stated as



According to Brady<sup>4</sup> "rusting occurs only if both oxygen and water are present. Iron won't rust in dry air or oxygen free water." Therefore, oxygen must be present in the WFI or else a corrosion cell must be present to liberate oxygen at the anode.

The next reaction is the oxidation of the hydrated ferrous oxide to ferric oxide Fe<sub>2</sub>O<sub>3</sub> to produce the magenta color:



Alternatively the reaction could be:



These reactions allow oxidation to a higher valence state without a decrease in pH by formation of gaseous molecular hydrogen. According to Dana<sup>5</sup>, the red oxide, hematite, can exist in several forms. One is "earthy", usually amorphous and is brownish red. Another is a

crystalline form that is deep red with a submetallic to nonmetallic luster or what we call magenta.

In the second set of samples iron oxidation appears to be two phase, the first involving dissolution of the chromium due to the presence of the chloride ion, the second the oxidation of the iron once the passive chromous oxide is dissolved:



According to Ehret<sup>6</sup>, "this gelatinous precipitate adheres only loosely to the iron" component of the stainless steel and "influences further corrosion in two ways": to retard corrosion "because it reduces the mobility of ions migrating to anodes and cathodes" that exist within the alloy formed by the "minute alloying elements that exist within the corrosion cell"; and "accelerates corrosion by blocking off certain areas of the iron from access to the iron". Therefore, "oxide is removed most energetically from those areas where rust (oxide) has accumulated and the supply of oxygen is the most limited". When this occurs pitting usually results. This may be an explanation for the red gelatinous oxide often found in WFI systems.

In the third set of samples the black color is due to the formation of iron sesquioxide,  $\text{Fe}_3\text{O}_4$ , or magnetite. According to Dana<sup>7</sup> this oxide is commonly, if not always, formed under conditions of high temperature. It is of the form  $\text{FeFe}_2\text{O}_4$  or  $\text{FeO}\cdot\text{Fe}_2\text{O}_3$  in which the ferrous iron occasionally may be replaced with nickel. Ehret<sup>8</sup> states that "this oxide is formed at very high temperatures by the action of air, steam or carbon dioxide upon iron". The reaction appears to be a two step reaction:



Because of the limited diffusion of oxygen, in this case because of the presence of chromous oxide, the two oxides possibly coexist in the same octahedral unit cell. In this rouge form some of the ferrous oxide may be replaced with nickel oxide. The SEM photograph clearly illustrates the octahedral crystal form.

## Discussion

In these rouging examples we are faced with what appears to be three different mechanisms for formation.

The first set of samples have the characteristic of an unaltered metallic surface below the rouge layer. The rouge could be removed by simple mechanical cleaning except for the magenta oxide. Under the oxide layer the electropolished luster is the same as a newly electropolished stainless steel and XPS analysis shows the same chromium/iron ratios are as high as an electropolished surface. Further, the oxides are not uniformly deposited throughout the system. They are heavier near the discharge of the centrifugal pump and decrease rapidly with distance from the pump inlet. After passing the take-off for the HP section the visible rouge totally disappears and the tubing has the silver luster of electropolished stainless steel. In the HP section the rouge is a magenta color in the inlet section, turning silver in the



remaining section. In the WFI section it is orange to red in color, eventually totally disappearing. In this system it appears that the corrosion product is transported from another location.

Because the composition of the corrosion product so closely matched the composition of stainless steel and because the SEM appearance of the particles was spherical, it seems that the origin is either the pump or the feed lines to the pump. The feed lines showed no evidence of rouging, therefore the source may be the impeller or volute of the centrifugal pump. At the flow rate for this system and the diameter of the pump impeller, the velocity of a water particle emerging from the tip of the impeller can exceed 180 feet per second (fps). According to Levy<sup>9</sup>, high chromium steels will have a critical erosion rate around 100 fps as illustrated in Figure 6. At this velocity the erosion rates increase ten fold. Although this figure is not for stainless steel, it representative of a high chromium ferrite, similar to the delta ferrite that may exist in many pump impeller castings. Uhlig<sup>10</sup> suggests that particles of metal may be "blasted" from the metallic surface by the shock waves generated by cavitation, a rather common condition with centrifugal pumps.

Thus, it seems that the conditions for erosion are present in many systems. The analytical data obtained here suggest that the rouge deposited originated from a different source than the stainless steel tubing used in the system. This concept is further strengthened by the progressive oxidation and concentration of the stainless steel particles as they migrate through the system. The presence of Teflon particles in the rouge also indicates the oxide particles and Teflon are being coprecipitated and that the oxides did not originate from the tube surfaces. A more complete set of experimental data supporting this observation are available elsewhere<sup>11</sup>.

The appearance of the second set of samples is completely different. The rouge appears more of a rust color and cannot be removed by mechanical cleaning, only by chemically dissolving it in nitric acid. When the rouge is dissolved a bright silver spot remains. In conventional corrosion mechanics this bright spot is referred to as an "active corrosion cell". The chromium/iron ratios are very low in these spots. Thus the surface of the stainless steel tubing has been altered, and the corrosion (or rouging) is occurring *in-situ*. Because this tubing was mechanically polished only and not chemically passivated, the chromium/iron ratios are low. The mechanism for this is described in the paper referenced earlier<sup>12</sup>.

The third set of samples is yet different in that the color is black and the iron oxide form is totally different. In the set described here the appearance is glossy, and in the one we only observed, from which we obtained no specimens for analysis, the appearance was powdery. Both of these were steam systems, operating at high temperatures. The oxide could not be removed by simple cleaning, only with reducing acids. When so removed the surface under the oxide had a low chromium/oxide ratio. Whether this was the result of the oxidation process or the cleaning operation cannot be proven. The observed powdery black system that we observed only was on a mechanically polished only tube and appears to be the high temperature analog of the second set of samples.

From the limited data we have obtained to date it appears that three different classes of rouge exist depending on the origin. These may be classified as follows:

**Class 1: Rouge from External Sources****A. Forms:**

i. Metal particles that are oxidized in WFI. These particles are generated from external surfaces by erosion or cavitation.

ii. Oxides from foreign sources such as carbon steel bolts, nuts or tie rods.

**B.** The particles and/or oxides are held onto the tubing surface by electrostatic attraction.

**C.** The stainless steel surface under the oxide is unaffected.

**D.** Composition of the oxide is not that of corroding stainless steel:

a. Particles and/or oxides appear to have a composition that matches that of the stainless steel from which it originated, e.g., a pump impeller.

**Class 2: Rouge from in-situ oxidation of the stainless steel surface where rouge is located.**

**A.** Results from low Cr/Fe ratio ( $<1$ ) and appears related to mechanical polished and non chemically passivated surfaces.

**B.** The surface under the rouge appears "active" with pits, crevice corrosion, etc.

**C.** Chlorides may play a major role, but this must be proven with additional tests.

**Class 3: Black Oxide Rouge**

**A.** Originates from High Temperature Steam Service

**B.** Appears to exist in two forms:

i. Glossy black over electropolished surfaces. These are very stable

ii. Powdery black. These are the high temperature analog of Class 2 Rouge. This rouge will rub off.

**C.** Rouge cannot be removed with simple cleaning, must be chemically removed.

**Summary**

A number of specimens were examined from three different rouged systems. Another condition was visually examined from a fourth system. From the analytical data obtained it appears that three different rouge systems exist. These include:

Class 1 Rouge where the corroding particles or oxides originate outside the system and are transported into the system

Class 2 Rouge which forms in-situ, usually on mechanically polished, non-passivated stainless steel surfaces

Class 3 Rouge which forms on the surfaces of high temperature steam systems.

In all the systems, the color and major contributor to the rouge appears to be iron. Proposed mechanisms for oxidation of the iron oxide forms isolated are presented.

Additional testing must be performed to verify the reactions and form a definitive mechanism.

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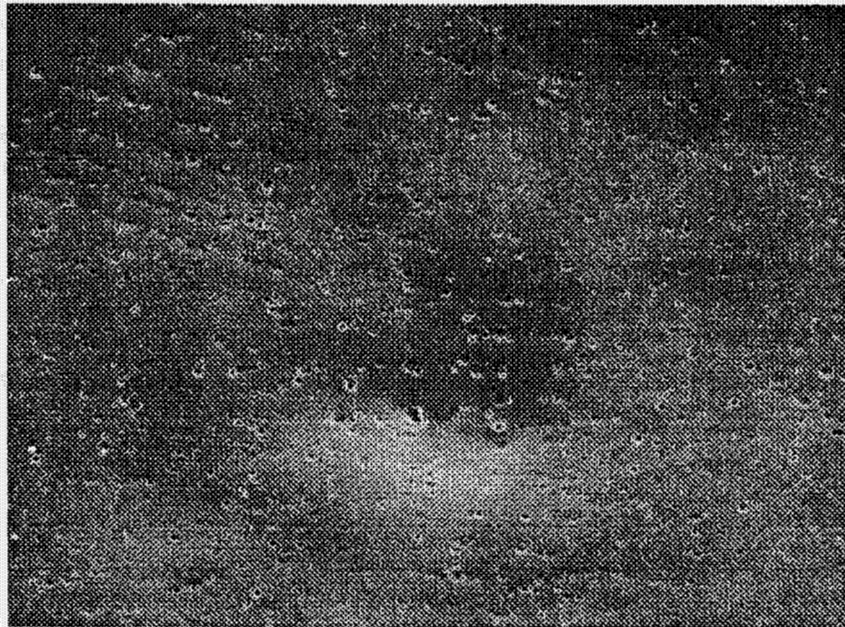


Figure 1: Small spherical particles on "silver" electropolished surface on Type 316L tubing from a WFI system. Origin appears to be external to the system. SEM 450X.



Figure 2: Denser population of spherical oxides on a "magenta" electropolished Type 316L tubing surface from a Hi-Purity system. Origin appears to external to the system. SEM 450X.



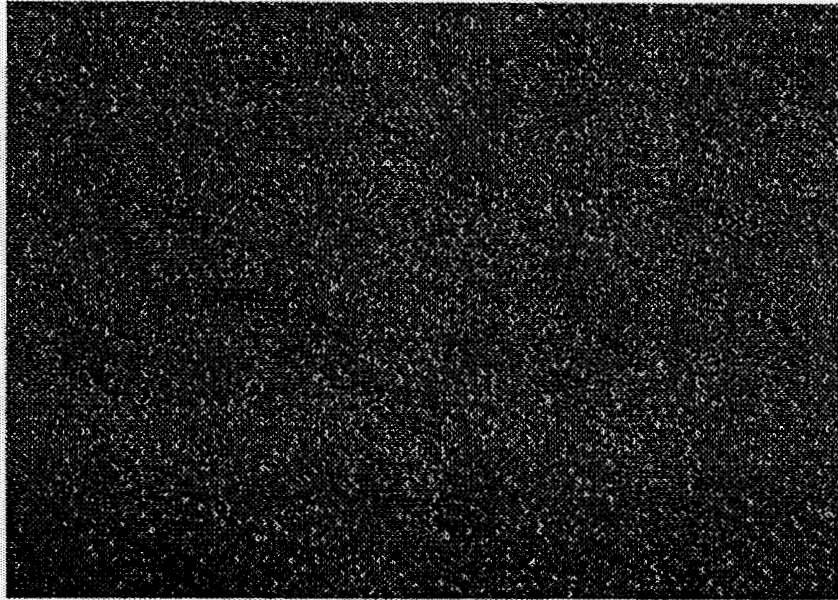


Figure 3: Heavy layer of Rouge on an "orange" electropolished Type 316L tubing surface from a WFI system. The particle shape is spherical and smaller than those on the "magenta" surface and more densely packed. SEM 450X.



Figure 4: Oxide particles on a mechanically polished non-passivated Type 304L stainless steel surface. Note the areas where the oxide "bubbles" have burst and the bare metal underneath. The white streaks under the top burst bubble probably represents an active stainless steel surface SEM 450X.





Figure 5: The highly crystalline surface of the gray-black glossy electropolished Type 316L stainless steel tube surface from a steam line. The subsurface crystals appear continuous and the top crystals appear to be joining together. Their crystal form is both octahedral and dodecahedral. This is typical for magnetite. SEM 450X.

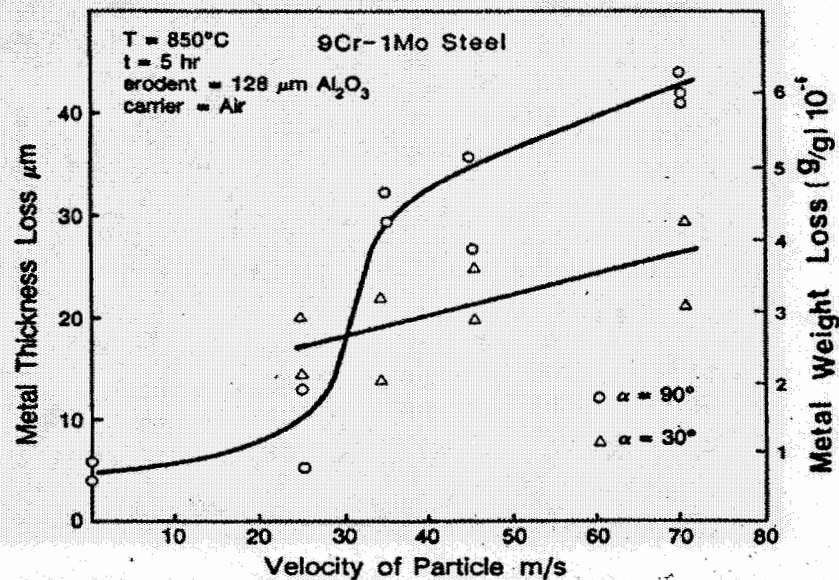


Figure 6: Metal thickness loss versus velocity illustrating critical erosion velocity point at ~ 100fps where the metal loss increases by a factor of nearly 10. From Levy<sup>9</sup>.